Fermilab

Particle Physics Division

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Title: PC4 ODH Assessment with 35 ton and LAPD

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Reviewer(s):

Key Words: LBNE, LAPD, 35t, ODH, PC4

Abstract Summary:

This is the ODH assessment for the 35 ton prototype cryostat, LAPD tank and associated purification equipment.

Applicable Codes:

1. *Fermilab Oxygen Deficiency Hazards (ODH), FESHM Chapter 5064, June, 2012*

I. INTRODUCTION

This ODH risk assessment is for the 35 ton prototype cryostat and LAPD tank and filtration equipment located in PC4. A Fatality Rate is computed to determine the ODH Classification. The ODH risk severity is computed from cryogen release probabilities and the associated impact on PC4's oxygen content. FESHM 5064 is used to determine the fatality risk factors. These fatality risk factors are combined with the cryogen release potentials to express the ODH risk as a total fatality rate with an associated ODH Class.

The 35 ton prototype cryostat is a membrane cryostat built to demonstrate that use of industrial membrane tank/cryostat technology can meet the requirements for a Particle Physics Detector.

The 35 ton prototype project will share the filtration equipment from the LAPD project. Valves are used to switch the filtration from LAPD to 35 ton and back.

II. SIZES AND VOLUMES

The PC4 building space is comprised of three rooms with free flow of air between them. Only the people space of floor to 6 foot is being counted since heavier than air gases are involved. The resulting volume for analysis is 60,249 cubic feet. Room dimensions[1] and calculation details are in the appendix A.

Liquid argon will be stored in PC4, in the 35 ton prototype cryostat and/or the LAPD tank. The 35 ton cryostat can hold 7,700 gallons (847,500 SCF) of liquid argon. The LAPD tank can hold 5,875 gallons (646,400 SCF) of liquid argon. Liquid argon is supplied from an argon trailer, located outside. Argon will be also be used as purge gas. The argon for purging will be supplied from argon Dewars, located outside.

Liquid nitrogen will provide cooling for the 35 ton and LAPD cryostat. The liquid nitrogen will be supplied from a liquid nitrogen trailer, located outside. LN2 trailer #22 is assumed to continue to be assigned to PC4 projects. This trailer can hold 4,000 gallons (364,800 SCF) of liquid nitrogen.

[1] Drawing 8-4-4-PS-2, REV A/B, Jan 4, 1974, Titled: Proton Laboratory Phase G

Filter regeneration will use combination gases, argon/hydrogen gas and nitrogen gas. The combination gases and argon/ hydrogen gas will be supplied from an outside tube trailer. The nitrogen gas will be supplied from the same outside, liquid nitrogen trailer supplying LN2 for cryostat cooling. The nitrogen gas comes from a vaporizer, located outside, before entering PC4.

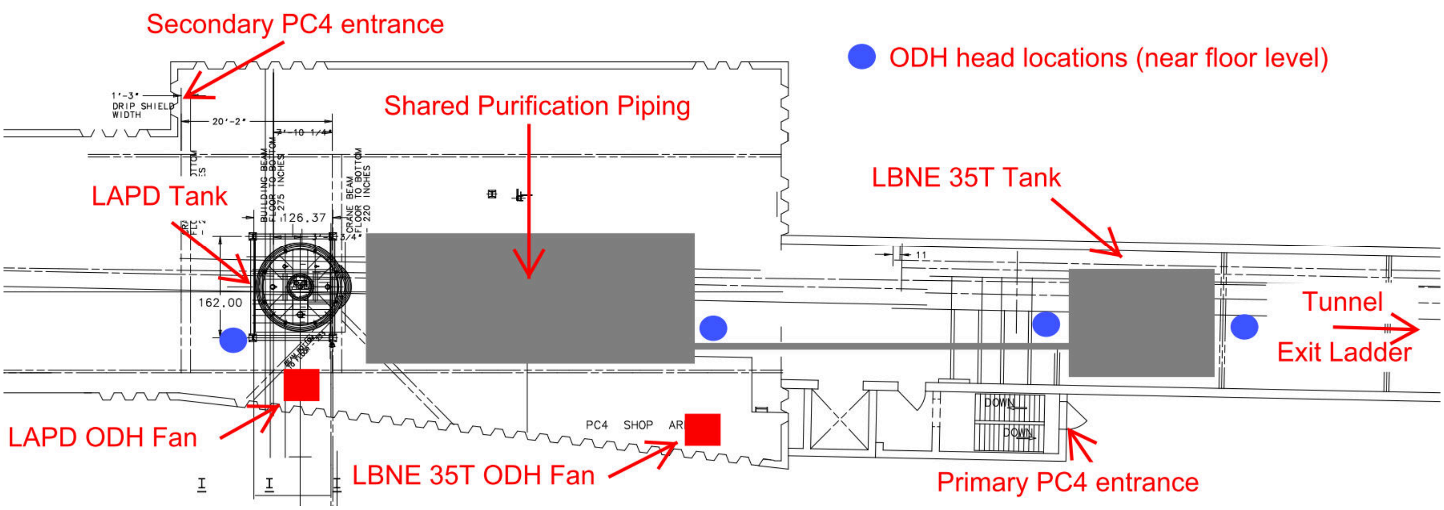
III. VENTILATION SYSTEMS

PC4 has does have existing basic ventilation. That ventilation is not counted in this ODH assessment.

IV. ODH DETECTORS

There will be four ODH detectors in PC4. The detectors will be located at ground level. These detectors are expected to detect an Argon or Nitrogen leak from the 35 ton cryostat or the LAPD tank or the shared filtration system. Detector locations are indicated in Figure 1.

Figure 1: ODH Head locations



V. LAPD ODH EXHAUST SYSTEM

The ODH exhaust system consists of two 3,000 cfm exhaust blowers. Fan placement is indicated in figure 1. Each blower has its own floor level intake and outlet duct that vents outside. When an ODH condition is signaled by any of the ODH detectors the following automated responses occur:

A. Activation of ODH alarm horns and lights

B. Activation of the ODH exhaust blowers

One blower is positioned near the LAPD tank and the second blower is positioned near the filtration piping. Both are at floor level to draw in heavier than air gases level and exhaust the gases outside. Fresh air is drawn in through existing openings near the ceiling on the East and West wall.

This ODH exhaust blower was previously tested and used as part of the LAPD project. There is sufficient existing building fresh air vent capacity. Additional air intakes are not needed.

When cryogens are present in PC4, the ODH exhaust blowers will be energized for a short period of time each day to confirm that the blowers are operational. Proper operation is confirmed by flow switches on each blower's outlet. All blower failure modes (power, fuse, motor, belt, or mechanical linkage) will be detected as a lack of pressure on the blower outlet. The LAPD PLC will inform the Fermi Facility Information Reporting Utility System (FIRUS) and use its auto dialer to inform 35 ton and LAPD personnel.

VI. SIGNIFICANT SOURCES OF CRYOGENS

The following are the significant sources of cryogens and gases which could produce ODH conditions in PC4 during operation of the 35 ton prototype work. These are the sources considered in the analysis of component failures or ruptures. The potential leak rates for argon and nitrogen are based on available pressure and leak size. The details can be found in the appendix.

LIQUID NITROGEN SUPPLY HEADER

The nitrogen supply header brings liquid nitrogen from the outside trailer. This header is part of the LAPD system and holds a finite nitrogen supply of 4,000 gallons (364,800 SCF).

Trailer Tank Normal Operating Range: 30-40 psig

Trailer Maximum Allowable Working Pressure: 50 psig

LIQUID ARGON SUPPLY HEADER

The argon supply header brings liquid argon from an outside liquid argon trailer during LAPD tank filling. This trailer holds a maximum argon supply of 4,000 gallons (442,000 SCF).

Liquid argon Dewars, located outside, will be supply argon for purge gas after LAPD tank filling is complete. There will be multiple connections available for hooking up liquid argon Dewars.

ARGON/HYDROGEN GAS HEADER

A gas header brings a 95% argon/5% hydrogen gas mixture from an outside trailer. This trailer has a finite capacity of 40,000 standard cubic feet of the argon/hydrogen gas mixture.

NITROGEN GAS HEADER

A nitrogen gas header provides nitrogen gas from an outside nitrogen ambient vaporizer. This vaporizer is fed by the same liquid nitrogen trailer gas identified above.

ARGON GAS HEADER

An argon gas header will provide argon gas from outside Dewars. This header will operate with a pressure regulator and the individual purge points will be fed by small stainless steel tubing and rotometer.

35 TON PROTOTYPE CRYOSTAT

The 35 ton prototype cryostat has a volume of 7,700 gallons. The liquid argon can be pumped from the cryostat through filtration steps and then back to the cryostat.

LAPD CRYOSTAT

The LAPD cryostat has a volume of 5,875 gallons. The liquid argon can be pumped from the cryostat through filtration steps and then back to the cryostat.

ARGON FILTRATION VESSELS

The filtration system is composed of two filter vessels. When the filtration system is operating, the filtration vessels would contain liquid argon. During filtration, a liquid argon pump inside the 35 ton cryostat can pump liquid argon to filtration, or an external pump can pump liquid argon from the LAPD cryostat to filtration. The filtration system can filter one cryostat at a time. During filtration, part of the source cryostats liquid argon will be contained in the filters. Each of the two filter vessels has an internal volume of 77 liters (20.3 gallons). When not filtering, the filter vessels are empty. Liquid argon boils off and is condensed by the condenser of the cryostat currently connected to the filtration system.

VII. FAILURES CONTRIBUTING TO ODH

A. Pressure Vessel – Leak and Failure

All of the small vessels, used in the cryostat cooling systems and in the argon filtration loop are pressure vessels. These vessels are the vacuum jacketed filters, vacuum jacketed pump, argon condenser and nitrogen phase separator.

The FESHM 5064 leak and disruptive failure rates are used. The release rate from a disruptive failure is estimated as the flow that can occur through the largest piping port on the vessel. This assumes the failure has totally severed that port.

B. 35 TON Prototype Cryostat – Leak and Failure

The 35 ton prototype cryostat is a membrane tank based on liquid natural gas (LNG) membrane tank technology. Membrane technology has been in use for over 30 years and is used for land and ship based LNG tanks. The membrane cryostat consists of a primary metal membrane within an insulated box, within a concrete tub. The membrane vendor provided leak and major failure rate data based on Quantitative Risk Analysis (QRA). These were compared against a published QRA and fault tree analysis for similar membrane technology. A leak failure rate of 1.18×10^{-8} per hour has been assigned to inner metal membrane technology. Details are contained in the appendix.

A disruptive membrane failure is a puncture or separation of the primary metal membrane. The liquid argon would still be contained by the additional layer of containment, but argon boil off rate would be significantly higher. In liquid argon service, the potential source of membrane puncture is dropping an argon pump within the cryostat and over pressure is the potential source for membrane separation. For this analysis, the membrane is assumed to be exposed under the pump locations 7.99×10^{-10} per hr. Details are in the appendix.

The 35 Ton cryostat will have a continuous purge of its insulation space with 1 CFM of argon gas. This purge will vent into PC4. This purge is not a credible ODH source in PC4 and has been left out of Table 1, since Table 1 does not include natural ventilation.

C. LAPD Tank – Leak and Failure

The LAPD tank is manufactured to API 620, appendix Q standards and has 100% radiography. This reduces its leak and catastrophic failure risks to a level comparable to pressure vessels. The pressure vessel leak and disruptive failure rates will be used.

For the vessel failure release rate the flow through a 2" schedule 40 port is used because the flow from a severed port below liquid level will exceed the release rate from a severed port in the vapor space because this is a low pressure tank.

D. Piping – Leak and Failure

Piping can fail by leaking or breaking. The leak failure can be further broken down into a small leak and a large leak. A small leak is an opening of 10 mm^2 or less. A large leak is an opening of 10mm^2 to 1000 mm^2. For this analysis, an average of 500 mm^2 is used to represent large leaks. Leak rates are from FESHM 5064.

E. Flanges and Conflats – Leak and Failure

All piping flanges will use reinforced or rigid gaskets. FESHM 5064, leak and flange separation (rupture) failure are used. Flanges are typically kept to a minimum in cryogenic service due to their leak potential.

Conflats are specific for low leaks under vacuum to low pressure conditions. For this analysis, flange leak and break failure rates are used to represent conflat failure risks. A generous number of conflats is assumed for this analysis.

F. *Relief Valve - Leak and Release*

Both cryostats have relief valves that are vented to the outside. The vent piping is handled as piping with leak and failure risks as noted previously.

The small relief valves protecting the filter vessels are assumed to vent inside PC4. One of these relief valves would release if a filter vessel is blocked in. A filter (22.5 gal) contains insufficient cryogen to exceed a fatality rate=0 impact on PC4 but two filters blocked in together with some piping would have sufficient cryogen. For this reason, multiple human errors were evaluated to determine the errors combinations that result in both filters being blocked in with liquid cryogen. Figure 2 contains the event tree with the combinations highlighted. The expected once every 30 days filter regeneration is used to calculate a per unit time rate from the per demand rate. The resulting risk rate for two filters blocked in with cryogen is then 2.71×10^{-7} per hour.

The small relief valves on the condenser and phase separator are assumed to vent inside PC4. For simplicity the same blocked in risk rate is used as was determined for the two filters block in risk above.

Trapped volume relief valves on the argon and nitrogen piping are also assumed to vent inside PC4. All piping trapped volumes contain insufficient cryogen to exceed a fatality rate=0 impact in PC4. Details are contained in the appendix.

G. *ODH Blower - Failure*

One or both ODH exhaust blowers/fans could fail because of, power failure, fuse opens prematurely, fan fails to start, fan fails while running, or ODH monitor fails. FESHM 5064 power failure rate is used to represent Fermi power reliability. Industrial failure rate data is used for fuse opens, fan fails to start, and fan fails while running. Vendor supplied failure rates are used for the ODH monitoring system and its control panel. To be conservative, breaker – spurious operation risk has also been included. The feed breaker – spurious operation risk is then double counted since it is also reflected in the Fermi site power reliability. A failure rate is determined for 50% ventilation (1 fan fails) and 0% ventilation (2 fans fail). The 50% ventilation rate is 1.25×10^{-10} per hour and 0% ventilation rate is 1.37×10^{-4} per hour. Details are in the appendix.

VIII. ODH CALCULATIONS

Oxygen concentrations are calculated using FESHM, 5064, equation 4 at time equal to infinity.

$$C = 0.21 \cdot \left(1 - \frac{R}{Q}\right)$$

- Q is the rate the ventilation is drawing out the contaminated atmosphere.
- R is the spill rate of the air displacing gas.
- C is the concentration of oxygen assuming perfect mixing.

It is assumed that any leak occurring during blower failure will drive the oxygen concentration to 0%, as time approaches infinity.

The fatality factor is per the graph in figure 1 of FESHM 5064. An equation was used to represent the graph in the ODH analysis, detailed in Table 1.

IX. RECOMMENDATIONS

With two 3,000 cfm ODH exhaust blowers, the total ODH fatality risk in PC4 is 2.45×10^{-8} per hour which is ODH Class 0 with operation of the 35 ton cryostat, LAPD and shared purification equipment. Operation of 35 ton or LAPD alone would have an even lower fatality risk and would still be ODH class 0.

While cryogens are present in PC4, both ODH blowers must be available to maintain ODH class 0.

X. REFERENCES

1. ***FESHM 5064, June, 2012***

2. ***Guidelines for Process Equipment Reliability Data, CCPS, 1989***

Figure 2: Event Tree for Human Errors blocking in both filters with cryogen - trapped V release

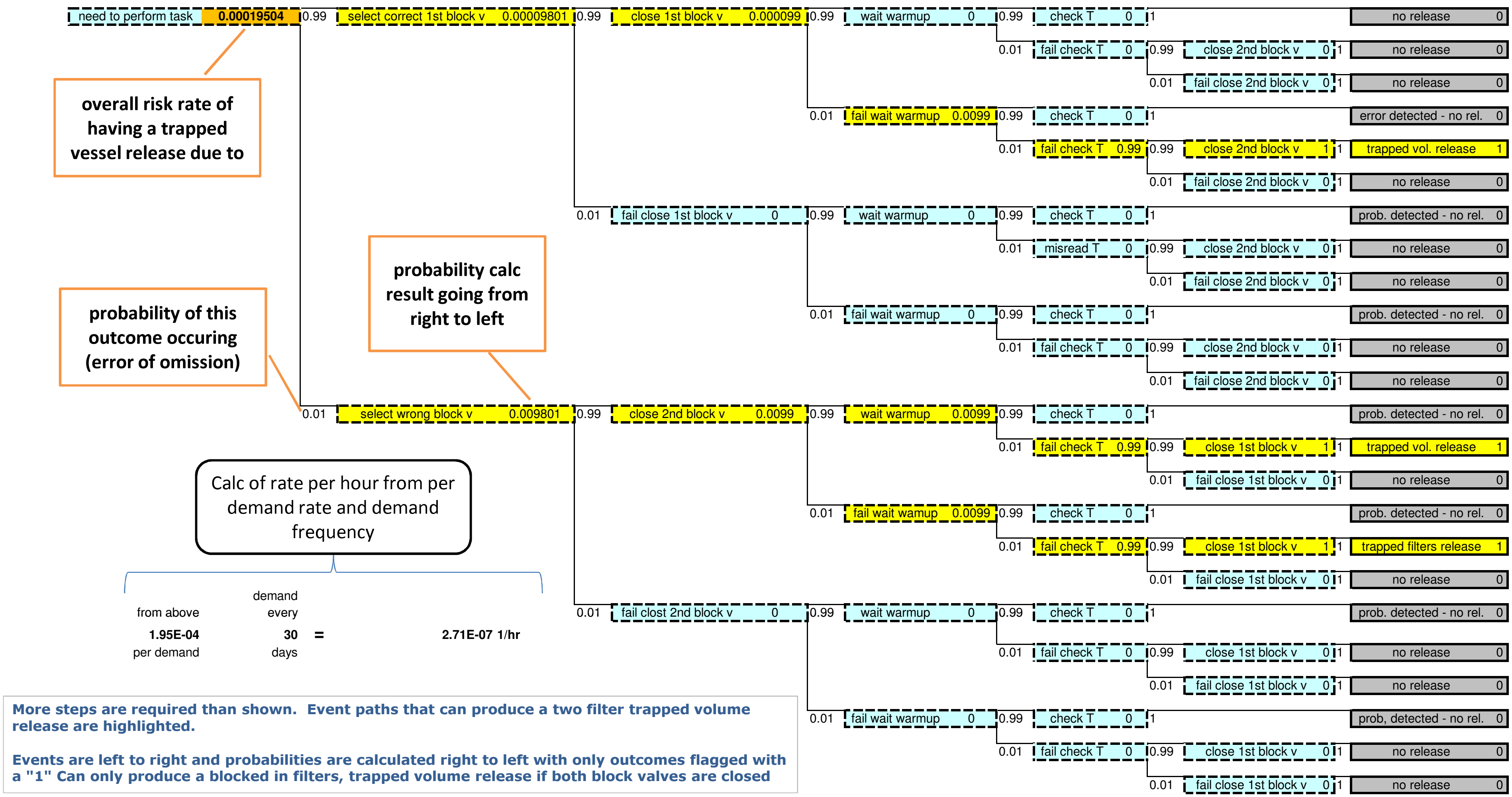


TABLE 1: 35 ton Cryostat in PC4, Oxygen Deficiency Hazard Assessment

People Space:	60,249	cu. ft. (based on 6ft height for people space)	
ODH Exhaust Fan1:	3,000	cu. ft./min	
ODH Exhaust Fan2:	3,000	cu. ft./min	fan2 capacity must be same as fan1 for table to be correct
ODH Exhaust Total:	6,000	cu. ft./min	HVAC Ventilation 0 cu. ft./min

Total Exhaust Affecting ODH	6,000	(vent. + ODH exhaust)		rev. 12/05/12
Prob. 100% ventilation:	0.999843	/hr	probability of 100% ventilation is calculated as 1 - P.50% - P.0%	
Prob. 50% ventilation:	2.20E-05	/hr	Prob. of 50% ventilation is 1 fan failed (fans have the same capacity)	
Prob. 0% (no) ventilation:	1.35E-04	/hr	Prob. of 0% ventilation is 2 (both) fans failed.	

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 0=fail 0 1=fail 1 2=fail 2 (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	PC4 Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes	
EQUIPMENT																				
35t Cryostat w/ 100% vent.																				
metal membrane	internal leak	1	1.18E-08	E	1.18E-08	847000	55	0	6000	15456	20.81%	-	20.81%	20.81%	0	0	0	-	taken as 2 x max boilup	0.0%
metal membrane	external leak	1	7.99E-10	E	7.99E-10	847000	2597	0	6000	326	11.91%	-	11.91%	11.91%	4.30E-3	3.43E-12	0	0.3	1mm x 0.33m membrane crack	0.0%
hatch	leak	1	1.18E-08	E	1.18E-08	847000	27	0	6000	30912	20.90%	-	20.90%	20.90%	0	0	0	-	limited by max boilup rate	0.0%
relief valve - relief event	error	1	0.00E+00	A	0.00E+00	847000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	847000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
relief valve	leak	1	1.00E+00	A	1.00E+00	847000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
conflat	leak	20	4.00E-07	B	8.00E-06	847000	4	0	6000	211750	20.99%	-	20.99%	20.99%	0	0	0	-	feedthru flanges	0.0%
conflat	break	20	1.00E-09	B	2.00E-08	847000	27	0	6000	30912	20.90%	-	20.90%	20.90%	0	0	0	-	limited by max boilup (2 kW)	0.0%
																				0.0%
35t Cryostat w/ 50% vent.																				0.0%
metal membrane	internal leak	1	1.18E-08	E	1.18E-08	847000	55	1	3000	15456	20.62%	-	20.62%	20.62%	0	0	0	-	taken as 2 x max boilup	0.0%
metal membrane	external leak	1	7.99E-10	E	7.99E-10	847000	2597	1	3000	326	2.82%	-	2.82%	2.82%	1.0	1.76E-14	0	0.2	1mm x 0.33m membrane crack	0.0%
hatch	leak	1	1.18E-08	E	1.18E-08	847000	27	1	3000	30912	20.81%	-	20.81%	20.81%	0	0	0	-	limited by max boilup rate	0.0%
relief valve - relief event	error	1	0.00E+00	A	0.00E+00	847000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	847000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
relief valve	leak	1	1.00E+00	A	1.00E+00	847000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
conflat	leak	20	4.00E-07	B	8.00E-06	847000	4	1	3000	211750	20.97%	-	20.97%	20.97%	0	0	0	-	feedthru flanges	0.0%
conflat	break	20	1.00E-09	B	2.00E-08	847000	27	1	3000	30912	20.81%	-	20.81%	20.81%	0	0	0	-	limited by max boilup (2 kW)	0.0%
																				0.0%
35t Cryostat w/ 0% vent.																				0.0%
metal membrane	internal leak	1	1.18E-08	E	1.18E-08	847000	55	2	0	15456	-	0.00%	0.00%	0.00%	1.0	1.59E-12	0	2.8	taken as 2 x max boilup	0.0%
metal membrane	external leak	1	7.99E-10	E	7.99E-10	847000	2597	2	0	326	-	0.00%	0.00%	0.00%	1.0	1.08E-13	0	0.1	1mm x 0.33m membrane crack	0.0%
hatch	leak	1	1.18E-08	E	1.18E-08	847000	27	2	0	30912	-	0.00%	0.00%	0.00%	1.0	1.59E-12	0	5.6	limited by max boilup rate	0.0%
relief valve - relief event	error	1	0.00E+00	A	0.00E+00	847000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	847000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 0=fail 0 1=fail 1 2=fail 2 (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	PC4 Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes	
relief valve	leak	1	1.00E+00	A	1.00E+00	847000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
conflat	leak	20	4.00E-07	B	8.00E-06	847000	4	2	0	211750	-	0.00%	0.00%	0.00%	1.0	1.08E-9	0	38.7	feedthru flanges	4.2%
conflat	break	20	1.00E-09	B	2.00E-08	847000	27	2	0	30912	-	0.00%	0.00%	0.00%	1.0	2.70E-12	0	5.6	limited by max boilup (2 kW)	0.0%
																				0.0%
LAPD Tank w/ 100% vent.																				
Tank	leak	1	8.00E-08	A	8.00E-08	645000	84	0	6000	7679	20.71%	-	20.71%	20.71%	0	0	0	-	small leak	0.0%
Tank	failure	1	5.00E-09	A	5.00E-09	645000	18103	0	6000	36	-	0.00%	0.00%	0.00%	1.0	5.00E-9	0	0.0	catastrophic failure	19.5%
relief valve - relief event	error	1	0.00E+00	A	0.00E+00	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
relief valve	leak	1	1.00E+00	A	1.00E+00	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
conflat	leak	30	3.00E-07	B	9.00E-06	645000	4	0	6000	161250	20.99%	-	20.99%	20.99%	0	0	0	-		0.0%
conflat	break	30	7.50E-10	B	2.25E-08	645000	19	0	6000	34309	20.93%	-	20.93%	20.93%	0	0	0	-	limited by max boil-up (2.4 kW)	0.0%
side manway	leak	1	4.00E-07	B	4.00E-07	645000	84	0	6000	7679	20.71%	-	20.71%	20.71%	0	0	0	-		0.0%
top manway	leak	1	4.00E-07	B	4.00E-07	645000	19	0	6000	34309	20.93%	-	20.93%	20.93%	0	0	0	-	limited by boil-up	0.0%
																				0.0%
LAPD Tank w/ 50% vent.																				0.0%
Tank	leak	1	8.00E-08	A	8.00E-08	645000	84	1	3000	7679	20.41%	-	20.41%	20.41%	0	0	0	-	small leak	0.0%
Tank	failure	1	5.00E-09	A	5.00E-09	645000	18103	1	3000	36	-	0.00%	0.00%	0.00%	1.0	1.10E-13	0	0.0	catastrophic failure	0.0%
relief valve - relief event	error	1	0.00E+00	A	0.00E+00	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
relief valve	leak	1	1.00E+00	A	1.00E+00	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
conflat	leak	30	3.00E-07	B	9.00E-06	645000	4	1	3000	161250	20.97%	-	20.97%	20.97%	0	0	0	-		
conflat	break	30	7.50E-10	B	2.25E-08	645000	19	1	3000	34309	20.87%	-	20.87%	20.87%	0	0	0	-	limited by max boil-up (2.4 kW)	
side manway	leak	1	4.00E-07	B	4.00E-07	645000	84	1	3000	7679	20.41%	-	20.41%	20.41%	0	0	0	-		0.0%
top manway	leak	1	4.00E-07	B	4.00E-07	645000	19	1	3000	34309	20.87%	-	20.87%	20.87%	0	0	0	-	limited by boil-up	0.0%
																				0.0%
LAPD Tank w/ 0% vent.																				0.0%
Tank	leak	1	8.00E-08	A	8.00E-08	645000	84	2	0	7679	-	0.00%	0.00%	0.00%	1.0	1.08E-11	0	1.8	small leak	0.0%
Tank	failure	1	5.00E-09	A	5.00E-09	645000	18103	2	0	36	-	0.00%	0.00%	0.00%	1.0	6.75E-13	0	0.0	catastrophic failure	0.0%
relief valve - relief event	error	1	0.00E+00	A	0.00E+00	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
relief valve	leak	1	1.00E+00	A	1.00E+00	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	vents outside	0.0%
conflat	leak	30	3.00E-07	B	9.00E-06	645000	4	2	0	161250	-	0.00%	0.00%	0.00%	1.0	1.22E-9	0	2321.9		
conflat	break	30	7.50E-10	B	2.25E-08	645000	19	2	0	34309	-	0.00%	0.00%	0.00%	1.0	3.04E-12	0	494.0	limited by max boil-up (2.4 kW)	
side manway	leak	1	4.00E-07	B	4.00E-07	645000	84	2	0	7679	-	0.00%	0.00%	0.00%	1.0	5.40E-11	0	1.8		0.2%
top manway	leak	1	4.00E-07	B	4.00E-07	645000	19	2	0	34309	-	0.00%	0.00%	0.00%	1.0	5.40E-11	0	8.2	limited by boil-up	0.2%
																				0.0%
35t Condenser w/ 100% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	847000	27	0	6000	30912	20.90%	-	20.90%	20.90%	0	0	0	-	limited by boil-up rate	0.0%

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 0=fail 0 1=fail 1 2=fail 2 (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	PC4 Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes	
VESSEL	failure	1	5.00E-09	A	5.00E-09	847000	27	0	6000	30912	20.90%	-	20.90%	20.90%	0	0	0	-	small LAr inventory / release limited by boil-up from main tank	0.0%
relief valve - relief event	error	1	2.71E-07	A	2.71E-07	2000	300	0	6000	7	20.49%	-	19.95%	20.49%	0	0	0	-	human error - blocks in cond.	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	847000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	1	1.00E+00		1.00E+00		0	0	6000		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
35t Condenser w/ 50% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	847000	27	1	3000	30912	20.81%	-	20.81%	20.81%	0	0	0	-	limited by boil-up rate	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09	847000	27	1	3000	30912	20.81%	-	20.81%	20.81%	0	0	0	-	small LAr inventory / release limited by boil-up from main tank	0.0%
relief valve - relief event	error	1	2.71E-07	A	2.71E-07	2000	300	1	3000	7	20.41%	-	18.90%	20.41%	0	0	0	-	human error - blocks in cond.	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	847000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	1	1.00E+00		1.00E+00	0	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
35t Condenser w/ 0% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	847000	27	2	0	30912	-	0.00%	0.00%	0.00%	1.0	1.08E-11	0	5.6	limited by boil-up rate	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09	847000	27	2	0	30912	-	0.00%	0.00%	0.00%	1.0	6.75E-13	0	5.6	small LAr inventory / release limited by boil-up from main tank	0.0%
relief valve - relief event	error	1	2.71E-07	A	2.71E-07	2000	300	2	0	7	-	20.31%	0.00%	20.31%	0	0	0	-	human error - blocks in cond.	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	847000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	1	1.00E+00		1.00E+00	0	0	2	0		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																			0	0.0%
LAPD Condenser w/ 100% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	645000	19	0	6000	34309	20.93%	-	20.93%	20.93%	0	0	0	-	limited by boil-up rate	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09	645000	19	0	6000	34309	20.93%	-	20.93%	20.93%	0	0	0	-	small LAr inventory / release limited by boil-up from main tank	0.0%
relief valve - relief event	error	1	2.71E-07	A	2.71E-07	2000	300	0	6000	7	20.49%	-	19.95%	20.49%	0	0	0	-	human error - blocks in cond.	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	1	1.00E+00		1.00E+00		0	0	6000		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
LAPD Condenser w/ 50% vent																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	645000	19	1	3000	34309	20.87%	-	20.87%	20.87%	0	0	0	-	limited by boil-up rate	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09	645000	19	1	3000	34309	20.87%	-	20.87%	20.87%	0	0	0	-	small LAr inventory / release limited by boil-up from main tank	0.0%

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 0=fail 0 1=fail 1 2=fail 2 (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	PC4 Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes	
relief valve - relief event	error	1	2.71E-07	A	2.71E-07	2000	300	1	3000	7	20.41%	-	18.90%	20.41%	0	0	0	-	human error - blocks in cond.	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	1	1.00E+00		1.00E+00	0	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
LAPD Condenser w/ 0% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	645000	19	2	0	34309	-	0.00%	0.00%	0.00%	1.0	1.08E-11	0	8.2	limited by boil-up rate	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09	645000	19	2	0	34309	-	0.00%	0.00%	0.00%	1.0	6.75E-13	0	8.2	small LAr inventory / release limited by boil-up from main tank	0.0%
relief valve - relief event	error	1	2.71E-07	A	2.71E-07	2000	300	2	0	7	-	20.31%	0.00%	20.31%	0	0	0	-	human error - blocks in cond.	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	1	1.00E+00		1.00E+00	0	0	2	0		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																			0	0.0%
N2 Phase Sep. (35t & LAPD) w/ 100% vent.																				0.0%
VESSEL	leak	2	8.00E-08	A	1.60E-07	346000	246	0	6000	1407	20.14%	-	20.14%	20.14%	0	0	0	-	small leak	0.0%
VESSEL	failure	2	5.00E-09	A	1.00E-08	346000	2517	0	6000	137	12.19%	-	12.19%	12.19%	2.63E-3	2.63E-11	0	0.4	pipe limited, trailer to p.sep.	0.1%
relief valve - relief event	error	2	2.71E-07	A	5.42E-07	2000	300	0	6000	7	20.49%	-	19.95%	20.49%	0	0	0	-	human error - blocks in sep.	0.0%
relief valve - relief event	premature open	2	0.00E+00		0.00E+00	346000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	2	1.00E-05	A	2.00E-05	346000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
N2 Phase Sep. (35t & LAPD) w/ 50% vent.																				0.0%
VESSEL	leak	2	8.00E-08	A	1.60E-07	346000	246	1	3000	1407	19.28%	-	19.28%	19.28%	0	0	0	-	small leak	0.0%
VESSEL	failure	2	5.00E-09	A	1.00E-08	346000	2517	1	3000	137	3.40%	-	3.38%	3.40%	1.0	2.20E-13	0	0.2	pipe limited, trailer to p.sep.	0.0%
relief valve - relief event	error	2	2.71E-07	A	5.42E-07	3000	300	1	3000	10	20.18%	-	18.90%	20.18%	0	0	0	-	human error - blocks in sep.	0.0%
relief valve - relief event	premature open	2	0.00E+00		0.00E+00	346000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	2	1.00E-05	A	2.00E-05	346000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
N2 Phase Sep. (35t & LAPD) w/ 0% vent.																				0.0%
VESSEL	leak	2	8.00E-08	A	1.60E-07	346000	246	2	0	1407	-	0.07%	0.00%	0.07%	1.0	2.16E-11	0	0.6	small leak	0.1%
VESSEL	failure	2	5.00E-09	A	1.00E-08	346000	2517	2	0	137	-	0.07%	0.00%	0.07%	1.0	1.35E-12	0	0.1	pipe limited, trailer to p.sep.	0.0%
relief valve - relief event	error	2	2.71E-07	A	5.42E-07	3000	300	2	0	10	-	19.98%	0.00%	19.98%	0	0	0	-	human error - blocks in sep.	0.0%
relief valve - relief event	premature open	2	0.00E+00		0.00E+00	346000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	2	1.00E-05	A	2.00E-05	346000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																0				0.0%
35t Argon Pump w/ 100% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08		0	0	6000		-	-	21.00%	21.00%	0	0	0	-	cotained by 35t cryostat	0.0%

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 0=fail 0 1=fail 1 2=fail 2 (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	PC4 Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes	
VESSEL	failure	1	5.00E-09	A	5.00E-09		0	0	6000		-	-	21.00%	21.00%	0	0	0	-	cotained by 35t cryostat	0.0%
																				0.0%
35t Argon Pump w/ 50% vent																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08		0	1	3000		-	-	21.00%	21.00%	0	0	0	-	cotained by 35t cryostat	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09		0	1	3000		-	-	21.00%	21.00%	0	0	0	-	cotained by 35t cryostat	0.0%
																				0.0%
35t Argon Pump w/ 0% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08		0	2	0		-	-	21.00%	21.00%	0	0	0	-	cotained by 35t cryostat	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09		0	2	0		-	-	21.00%	21.00%	0	0	0	-	cotained by 35t cryostat	0.0%
																				0.0%
LAPD Argon Pump w/ 100% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	645000	271	0	6000	2380	20.05%	-	20.05%	20.05%	0	0	0	-	small leak	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09	645000	1695	0	6000	381	15.07%	-	15.07%	15.07%	1.70E-5	8.51E-14	0	0.5	limited by max LAPD pump rate	0.0%
																				0.0%
LAPD Argon Pump w/ 50% vent																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	645000	271	1	3000	2380	19.10%	-	19.10%	19.10%	0	0	0	-	small leak	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09	645000	1695	1	3000	381	9.14%	-	9.14%	9.14%	0.56	6.12E-14	0	0.5	limited by max LAPD pump rate	0.0%
																				0.0%
LAPD Argon Pump w/ 0% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	645000	271	2	0	2380	-	0.00%	0.00%	0.00%	1.0	1.08E-11	0	0.6	small leak	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09	645000	1695	2	0	381	-	0.00%	0.00%	0.00%	1.0	6.75E-13	0	0.1	limited by max LAPD pump rate	0.0%
																				0.0%
Filter Vessels w/ 100% vent.																				0.0%
VESSEL	leak	2	8.00E-08	A	1.60E-07	645000	271	0	6000	2380	20.05%	-	20.05%	20.05%	0	0	0	-	small leak	0.0%
VESSEL	failure	2	5.00E-09	A	1.00E-08	645000	3170	0	6000	203	9.91%	-	9.91%	9.91%	0.14	1.44E-9	0	0.3	max credible flow into filter	5.6%
VENT VALVE	error	2	0.00E+00	A	0.00E+00	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	human error - vents outside	0.0%
relief valve - 2 filter relief event	error	1	2.71E-07	A	2.71E-07	2300	300	0	6000	8	20.44%	-	19.95%	20.44%	0	0	0	-	human error - blocks in filter	0.0%
relief valve - relief event	premature open	2	0.00E+00		0.00E+00	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	2	1.00E-05	A	2.00E-05	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
Filter Vessels w/ 50% vent																				0.0%
VESSEL	leak	2	8.00E-08	A	1.60E-07	645000	271	1	3000	2380	19.10%	-	19.10%	19.10%	0	0	0	-	small leak	0.0%
VESSEL	failure	2	5.00E-09	A	1.00E-08	645000	3170	1	3000	203	-	0.00%	0.00%	0.00%	1.0	2.20E-13	0	0.0	max credible flow into filter	0.0%
VENT VALVE	error	2	0.00E+00	A	0.00E+00	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	human error - vents outside	0.0%
relief valve - 2 filter relief event	error	1	2.71E-07	A	2.71E-07	2300	300	1	3000	8	20.33%	-	18.90%	20.33%	0	0	0	-	human error - blocks in filter	0.0%
relief valve - relief event	premature open	2	0.00E+00		0.00E+00	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 0=fail 0 1=fail 1 2=fail 2 (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	PC4 Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes	
relief valve	leak	2	1.00E-05	A	2.00E-05	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
Filter Vessels w/ 0% vent.																				0.0%
VESSEL	leak	2	8.00E-08	A	1.60E-07	645000	271	2	0	2380	-	0.00%	0.00%	0.00%	1.0	2.16E-11	0	0.6	small leak	0.1%
VESSEL	failure	2	5.00E-09	A	1.00E-08	645000	3170	2	0	203	-	0.00%	0.00%	0.00%	1.0	1.35E-12	0	0.0	max credible flow into filter	0.0%
VENT VALVE	error	2	0.00E+00	A	0.00E+00	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	human error - vents outside	0.0%
relief valve - 2 filter relief event	error	1	2.71E-07	A	2.71E-07	2300	300	2	0	8	-	20.21%	0.00%	20.21%	0	0	0	-	human error - blocks in filter	0.0%
relief valve - relief event	premature open	2	0.00E+00		0.00E+00	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	2	1.00E-05	A	2.00E-05	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
Purity Monitor w/ 100% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	645000	271	0	6000	2380	20.05%	-	20.05%	20.05%	0	0	0	-	small leak	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09	645000	3170	0	6000	203	9.91%	-	9.91%	9.91%	0.14	7.21E-10	0	0.3	max credible flow into monitor	2.8%
VENT VALVE	error	1	0.00E+00	A	0.00E+00	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	human error - vents outside	0.0%
relief valve - relief event	error	1	2.71E-07	A	2.71E-07	2300	300	0	6000	8	20.44%	-	19.95%	20.44%	0	0	0	-	human error - blocks in filter	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	1	1.00E-05	A	1.00E-05	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
Purity Monitor w/ 50% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	645000	271	1	3000	2380	19.10%	-	19.10%	19.10%	0	0	0	-	small leak	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09	645000	3170	1	3000	203	-	0.00%	0.00%	0.00%	1.0	1.10E-13	0	0.0	max credible flow into monitor	0.0%
VENT VALVE	error	1	0.00E+00	A	0.00E+00	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	human error - vents outside	0.0%
relief valve - relief event	error	1	2.71E-07	A	2.71E-07	2300	300	1	3000	8	20.33%	-	18.90%	20.33%	0	0	0	-	human error - blocks in filter	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	1	1.00E-05	A	1.00E-05	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
Purity Monitor w/ 0% vent.																				0.0%
VESSEL	leak	1	8.00E-08	A	8.00E-08	645000	271	2	0	2380	-	0.00%	0.00%	0.00%	1.0	1.08E-11	0	0.6	small leak	0.0%
VESSEL	failure	1	5.00E-09	A	5.00E-09	645000	3170	2	0	203	-	0.00%	0.00%	0.00%	1.0	6.75E-13	0	0.0	max credible flow into monitor	0.0%
VENT VALVE	error	1	0.00E+00	A	0.00E+00	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	human error - vents outside	0.0%
relief valve - relief event	error	1	2.71E-07	A	2.71E-07	2300	300	2	0	8	-	20.21%	0.00%	20.21%	0	0	0	-	human error - blocks in filter	0.0%
relief valve - relief event	premature open	1	0.00E+00		0.00E+00	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
relief valve	leak	1	1.00E-05	A	1.00E-05	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	meets API-527, leak <0.001 cfm	0.0%
																				0.0%
PIPING																				0.0%

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 0=fail 0 1=fail 1 2=fail 2 (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	PC4 Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes	
N2 Supply w/ 100% vent.																				0.0%
PIPES < 2"	leak, small	100	3.05E-10	B	3.05E-08	346000	246	0	6000	1407	20.14%	-	20.14%	20.14%	0	0	0	-		0.0%
PIPES < 2"	leak, large	100	3.05E-11	B	3.05E-09	346000	3540	0	6000	98	8.61%	-	8.61%	8.61%	1.0	3.05E-9	0	0.2	max credible flow	11.9%
PIPES < 2"	break	100	9.14E-12	B	9.14E-10	346000	3540	0	6000	98	8.61%	-	8.61%	8.61%	1.0	9.14E-10	0	0.2	max credible flow	3.6%
Flanges	leak	4	4.00E-07	B	1.60E-06	346000	246	0	6000	1407	20.14%	-	20.14%	20.14%	0	0	0	-		0.0%
Flanges	break	4	1.00E-09	B	4.00E-09	346000	3540	0	6000	98	8.61%	-	8.61%	8.61%	1.0	4.00E-9	0	0.2	max credible flow	15.6%
VALVE	leak	4	1.00E-08	A	4.00E-08	346000	246	0	6000	1407	20.14%	-	20.14%	20.14%	0	0	0	-		0.0%
vent valve	error	1	2.76E-09	A	2.76E-09	346000	1000	0	6000	346	17.50%	-	17.50%	17.50%	2.40E-7	6.63E-16	0	0.9	human error - per HRA	0.0%
Trapped V reliefs - relief event	error	12	1.25E-05	A	1.50E-04	1000	10	0	6000	100	20.97%	-	20.97%	20.97%	0	0	0	-	human err - creates trapped V	0.0%
Trapped V reliefs - relief event	premature open	12	0.00E+00	H	0.00E+00	346000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
Trapped V reliefs	leak	12	1.00E+00	A	1.20E+01	346000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	circleseal leak=0 below reseal P	0.0%
																				0.0%
N2 Supply w/ 50% vent.																				0.0%
PIPES < 2"	leak, small	100	3.05E-10	B	3.05E-08	346000	246	1	3000	1407	19.28%	-	19.28%	19.28%	0	0	0	-		0.0%
PIPES < 2"	leak, large	100	3.05E-11	B	3.05E-09	346000	3540	1	3000	98	-	0.07%	0.00%	0.07%	1.0	6.71E-14	0	0.0	max credible flow	0.0%
PIPES < 2"	break	100	9.14E-12	B	9.14E-10	346000	3540	1	3000	98	-	0.07%	0.00%	0.07%	1.0	2.01E-14	0	0.0	max credible flow	0.0%
Flanges	leak	4	4.00E-07	B	1.60E-06	346000	246	1	3000	1407	19.28%	-	19.28%	19.28%	0	0	0	-		0.0%
Flanges	break	4	1.00E-09	B	4.00E-09	346000	3540	1	3000	98	-	0.07%	0.00%	0.07%	1.0	8.80E-14	0	0.0	max credible flow	0.0%
VALVE	leak	4	1.00E-08	A	4.00E-08	346000	246	1	3000	1407	19.28%	-	19.28%	19.28%	0	0	0	-		0.0%
vent valve	error	1	2.76E-09	A	2.76E-09	346000	1000	1	3000	346	14.00%	-	14.00%	14.00%	1.11E-4	6.71E-18	0	0.9	human error - per HRA	0.0%
Trapped V reliefs - relief event	error	12	1.25E-05	A	1.50E-04	1000	10	1	3000	100	20.93%	-	20.93%	20.93%	0	0	0	-	human err - creates trapped V	0.0%
Trapped V reliefs - relief event	premature open	12	0.00E+00	H	0.00E+00	346000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
Trapped V reliefs	leak	12	1.00E+00	A	1.20E+01	346000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	circleseal leak=0 below reseal P	0.0%
																				0.0%
N2 Supply w/ 0% vent.																				0.0%
PIPES < 2"	leak, small	100	3.05E-10	B	3.05E-08	346000	246	2	0	1407	-	0.07%	0.00%	0.07%	1.0	4.12E-12	0	0.6		0.0%
PIPES < 2"	leak, large	100	3.05E-11	B	3.05E-09	346000	3540	2	0	98	-	0.07%	0.00%	0.07%	1.0	4.12E-13	0	0.0	max credible flow	0.0%
PIPES < 2"	break	100	9.14E-12	B	9.14E-10	346000	3540	2	0	98	-	0.07%	0.00%	0.07%	1.0	1.23E-13	0	0.0	max credible flow	0.0%
Flanges	leak	4	4.00E-07	B	1.60E-06	346000	246	2	0	1407	-	0.07%	0.00%	0.07%	1.0	2.16E-10	0	0.6		0.8%
Flanges	break	4	1.00E-09	B	4.00E-09	346000	3540	2	0	98	-	0.07%	0.00%	0.07%	1.0	5.40E-13	0	0.0	max credible flow	0.0%
VALVE	leak	4	1.00E-08	A	4.00E-08	346000	246	2	0	1407	-	0.07%	0.00%	0.07%	1.0	5.40E-12	0	0.6		0.0%
vent valve	error	1	2.76E-09	A	2.76E-09	346000	1000	2	0	346	-	0.07%	0.00%	0.07%	1.0	3.73E-13	0	0.2	human error - per HRA	0.0%
Trapped V reliefs - relief event	error	12	1.25E-05	A	1.50E-04	1000	10	2	0	100	-	20.65%	0.00%	20.65%	0	0	0	-	human err - creates trapped V	0.0%
Trapped V reliefs - relief event	premature open	12	0.00E+00	H	0.00E+00	346000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
Trapped V reliefs	leak	12	1.00E+00	A	1.20E+01	346000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	circleseal leak=0 below reseal P	0.0%
																				0.0%
N2 vent gas w/ 100% vent.																				0.0%
PIPES < 2"	leak, small	100	3.05E-10	B	3.05E-08	346000	21	0	6000	16476	20.93%	-	20.93%	20.93%	0	0	0	-		0.0%
PIPES < 2"	leak, large	100	3.05E-11	B	3.05E-09	346000	1032	0	6000	335	17.39%	-	17.39%	17.39%	2.92E-7	8.91E-16	0	0.9		0.0%
PIPES < 2"	break	100	9.14E-12	B	9.14E-10	346000	1259	0	6000	275	16.59%	-	16.59%	16.59%	1.18E-6	1.07E-15	0	0.7		0.0%
Flanges	leak	1	4.00E-07	B	4.00E-07	346000	21	0	6000	16476	20.93%	-	20.93%	20.93%	0	0	0	-		0.0%

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 0=fail 0 1=fail 1 2=fail 2 (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	PC4 Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes	
Flanges	break	1	1.00E-09	B	1.00E-09	346000	723	0	6000	479	18.47%	-	18.47%	18.47%	0	0	0	-		0.0%
VALVE	leak	1	1.00E-08	A	1.00E-08	346000	21	0	6000	16476	20.93%	-	20.93%	20.93%	0	0	0	-	small leak	0.0%
																				0.0%
N2 vent gas w/ 50% vent																				0.0%
PIPES < 2"	leak, small	100	3.05E-10	B	3.05E-08	346000	21	1	3000	16476	20.85%	-	20.85%	20.85%	0	0	0	-		0.0%
PIPES < 2"	leak, large	100	3.05E-11	B	3.05E-09	346000	1032	1	3000	335	13.78%	-	13.78%	13.78%	1.64E-4	1.10E-17	0	0.9		0.0%
PIPES < 2"	break	100	9.14E-12	B	9.14E-10	346000	1259	1	3000	275	12.19%	-	12.19%	12.19%	2.65E-3	5.32E-17	0	0.7		0.0%
Flanges	leak	1	4.00E-07	B	4.00E-07	346000	21	1	3000	16476	20.85%	-	20.85%	20.85%	0	0	0	-		0.0%
Flanges	break	1	1.00E-09	B	1.00E-09	346000	723	1	3000	479	15.94%	-	15.94%	15.94%	3.70E-6	8.14E-20	0	1.3		0.0%
VALVE	leak	1	1.00E-08	A	1.00E-08	346000	21	1	3000	16476	20.85%	-	20.85%	20.85%	0	0	0	-	small leak	0.0%
																				0.0%
N2 vent gas w/ 0% vent.																				0.0%
PIPES < 2"	leak, small	100	3.05E-10	B	3.05E-08	346000	21	2	0	16476	-	0.07%	0.00%	0.07%	1.0	4.12E-12	0	7.4		0.0%
PIPES < 2"	leak, large	100	3.05E-11	B	3.05E-09	346000	1032	2	0	335	-	0.07%	0.00%	0.07%	1.0	4.12E-13	0	0.1		0.0%
PIPES < 2"	break	100	9.14E-12	B	9.14E-10	346000	1259	2	0	275	-	0.07%	0.00%	0.07%	1.0	1.23E-13	0	0.1		0.0%
Flanges	leak	1	4.00E-07	B	4.00E-07	346000	21	2	0	16476	-	0.07%	0.00%	0.07%	1.0	5.40E-11	0	7.4		0.2%
Flanges	break	1	1.00E-09	B	1.00E-09	346000	723	2	0	479	-	0.07%	0.00%	0.07%	1.0	1.35E-13	0	0.2		0.0%
VALVE	leak	1	1.00E-08	A	1.00E-08	346000	21	2	0	16476	-	0.07%	0.00%	0.07%	1.0	1.35E-12	0	7.4	small leak	0.0%
																				0.0%
Argon Loop w/ 100% vent.																				0.0%
PIPES < 2"	leak, small	500	3.05E-10	B	1.53E-07	645000	271	0	6000	2380	20.05%	-	20.05%	20.05%	0	0	0	-		0.0%
PIPES < 2"	leak, large	500	3.05E-11	B	1.53E-08	645000	3170	0	6000	203	9.91%	-	9.91%	9.91%	0.14	2.20E-9	0	0.3	max credible, pres drop limited	8.6%
PIPES < 2"	break	500	9.14E-12	B	4.57E-09	645000	3170	0	6000	203	9.91%	-	9.91%	9.91%	0.14	6.59E-10	0	0.3	max credible, pres drop limited	2.6%
Flanges	leak	24	4.00E-07	B	9.60E-06	645000	271	0	6000	2380	20.05%	-	20.05%	20.05%	0	0	0	-		0.0%
Flanges	break	24	1.00E-09	B	2.40E-08	645000	3170	0	6000	203	9.91%	-	9.91%	9.91%	0.14	3.46E-9	0	0.3	max credible, pres drop limited	13.5%
VALVE	leak	24	1.00E-08	A	2.40E-07	645000	271	0	6000	2380	20.05%	-	20.05%	20.05%	0	0	0	-	small leak	0.0%
Trapped V reliefs - relief event	error	6	1.25E-05	A	7.50E-05	1000	10	0	6000	100	20.97%	-	20.97%	20.97%	0	0	0	-	human err - creates trapped V	0.0%
Trapped V reliefs - relief event	premature open	6	0.00E+00		0.00E+00	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
Trapped V reliefs	leak	6	1.00E-05	A	6.00E-05	645000	0	0	6000		-	-	21.00%	21.00%	0	0	0	-	circleseal leak=0 below reseal P	0.0%
																				0.0%
Argon Loop w/ 50% vent.																				0.0%
PIPES < 2"	leak, small	500	3.05E-10	B	1.53E-07	645000	271	1	3000	2380	19.10%	-	19.10%	19.10%	0	0	0	-		0.0%
PIPES < 2"	leak, large	500	3.05E-11	B	1.53E-08	645000	3170	1	3000	203	-	0.00%	0.00%	0.00%	1.0	3.36E-13	0	0.0	max credible, pres drop limited	0.0%
PIPES < 2"	break	500	9.14E-12	B	4.57E-09	645000	3170	1	3000	203	-	0.00%	0.00%	0.00%	1.0	1.01E-13	0	0.0	max credible, pres drop limited	0.0%
Flanges	leak	24	4.00E-07	B	9.60E-06	645000	271	1	3000	2380	19.10%	-	19.10%	19.10%	0	0	0	-		0.0%
Flanges	break	24	1.00E-09	B	2.40E-08	645000	3170	1	3000	203	-	0.00%	0.00%	0.00%	1.0	5.28E-13	0	0.0	max credible, pres drop limited	0.0%
VALVE	leak	24	1.00E-08	A	2.40E-07	645000	271	1	3000	2380	19.10%	-	19.10%	19.10%	0	0	0	-	small leak	0.0%
Trapped V reliefs - relief event	error	6	1.25E-05	A	7.50E-05	1000	10	1	3000	100	20.93%	-	20.93%	20.93%	0	0	0	-	human err - creates trapped V	0.0%
Trapped V reliefs - relief event	premature open	6	0.00E+00		0.00E+00	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
Trapped V reliefs	leak	6	1.00E-05	A	6.00E-05	645000	0	1	3000		-	-	21.00%	21.00%	0	0	0	-	circleseal leak=0 below reseal P	0.0%
																				0.0%
Argon Loop w/ 0% vent.																				0.0%

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 0=fail 0 1=fail 1 2=fail 2 (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	PC4 Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes	
PIPES < 2"	leak, small	500	3.05E-10	B	1.53E-07	645000	271	2	0	2380	-	0.00%	0.00%	0.00%	1.0	2.06E-11	0	0.6		0.1%
PIPES < 2"	leak, large	500	3.05E-11	B	1.53E-08	645000	3170	2	0	203	-	0.00%	0.00%	0.00%	1.0	2.06E-12	0	0.0	max credible, pres drop limited	0.0%
PIPES < 2"	break	500	9.14E-12	B	4.57E-09	645000	3170	2	0	203	-	0.00%	0.00%	0.00%	1.0	6.17E-13	0	0.0	max credible, pres drop limited	0.0%
Flanges	leak	24	4.00E-07	B	9.60E-06	645000	271	2	0	2380	-	0.00%	0.00%	0.00%	1.0	1.30E-9	0	0.6		5.0%
Flanges	break	24	1.00E-09	B	2.40E-08	645000	3170	2	0	203	-	0.00%	0.00%	0.00%	1.0	3.24E-12	0	0.0	max credible, pres drop limited	0.0%
VALVE	leak	24	1.00E-08	A	2.40E-07	645000	271	2	0	2380	-	0.00%	0.00%	0.00%	1.0	3.24E-11	0	0.6	small leak	0.1%
Trapped V reliefs - relief event	error	6	1.25E-05	A	7.50E-05	1000	10	2	0	100	-	20.65%	0.00%	20.65%	0	0	0	-	human err - creates trapped V	0.0%
Trapped V reliefs - relief event	premature open	6	0.00E+00		0.00E+00	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	operating press. < 80% of setpoint - no premature open	0.0%
Trapped V reliefs	leak	6	1.00E-05	A	6.00E-05	645000	0	2	0		-	-	21.00%	21.00%	0	0	0	-	circleseal leak=0 below reseal P	0.0%
																				0.0%
Vent Pipes w/ 100% vent.																				0.0%
PIPES, < 2"	leak, small	200	3.05E-10	B	6.10E-08	645000	1	0	6000	645000	21.00%	-	21.00%	21.00%	0	0	0	-	listed as 1 cfm, actual 0.22 cfm	0.0%
PIPES, < 2"	leak, large	200	3.05E-11	B	6.10E-09	645000	11	0	6000	58636	20.96%	-	20.96%	20.96%	0	0	0	-	limited by boil-up (35t)	0.0%
PIPES, < 2"	break	200	9.14E-12	B	1.83E-09	645000	27	0	6000	23540	20.90%	-	20.90%	20.90%	0	0	0	-	limited by boil-up (35t)	0.0%
PIPES, > 2"	leak, small	60	3.05E-10	B	1.83E-08	645000	1	0	6000	645000	21.00%	-	21.00%	21.00%	0	0	0	-		0.0%
PIPES, > 2"	leak, large	60	3.05E-11	B	1.83E-09	645000	27	0	6000	23540	20.90%	-	20.90%	20.90%	0	0	0	-	limited by boil-up (35t)	0.0%
PIPES, > 2"	break	60	9.14E-12	B	5.48E-10	645000	27	0	6000	23540	20.90%	-	20.90%	20.90%	0	0	0	-	limited by boil-up (35t)	0.0%
Flanges	leak	12	4.00E-07	B	4.80E-06	1000	1	0	6000	1000	21.00%	-	21.00%	21.00%	0	0	0	-		0.0%
Flanges	break	12	1.00E-09	B	1.20E-08	645000	23	0	6000	28043	20.92%	-	20.92%	20.92%	0	0	0	-		0.0%
VALVE	leak	12	1.00E-08	A	1.20E-07	645000	1	0	6000	645000	21.00%	-	21.00%	21.00%	0	0	0	-		0.0%
																				0.0%
Vent Pipes w/ 50% vent																				0.0%
PIPES, < 2"	leak, small	200	3.05E-10	B	6.10E-08	645000	1	1	3000	645000	20.99%	-	20.99%	20.99%	0	0	0	-	listed as 1 cfm, actual 0.22 cfm	0.0%
PIPES, < 2"	leak, large	200	3.05E-11	B	6.10E-09	645000	11	1	3000	58636	20.92%	-	20.92%	20.92%	0	0	0	-	limited by boil-up (35t)	0.0%
PIPES, < 2"	break	200	9.14E-12	B	1.83E-09	645000	27	1	3000	23540	20.81%	-	20.81%	20.81%	0	0	0	-	limited by boil-up (35t)	0.0%
PIPES, > 2"	leak, small	60	3.05E-10	B	1.83E-08	645000	1	1	3000	645000	20.99%	-	20.99%	20.99%	0	0	0	-		0.0%
PIPES, > 2"	leak, large	60	3.05E-11	B	1.83E-09	645000	27	1	3000	23540	20.81%	-	20.81%	20.81%	0	0	0	-	limited by boil-up (35t)	0.0%
PIPES, > 2"	break	60	9.14E-12	B	5.48E-10	645000	27	1	3000	23540	20.81%	-	20.81%	20.81%	0	0	0	-	limited by boil-up (35t)	0.0%
Flanges	leak	12	4.00E-07	B	4.80E-06	1000	11	1	3000	91	20.92%	-	20.92%	20.92%	0	0	0	-		0.0%
Flanges	break	12	1.00E-09	B	1.20E-08	645000	23	1	3000	28043	20.84%	-	20.84%	20.84%	0	0	0	-	0	0.0%
VALVE	leak	12	1.00E-08	A	1.20E-07	645000	1	1	3000	645000	20.99%	-	20.99%	20.99%	0	0	0	-		0.0%
																				0.0%
Vent Pipes w/ 0% vent.																				0.0%
PIPES, < 2"	leak, small	200	3.05E-10	B	6.10E-08	645000	1	2	0	645000	-	0.00%	0.00%	0.00%	1.0	8.24E-12	0	154.8	exceeds credible time with 0% ventilation	0.0%
PIPES, < 2"	leak, large	200	3.05E-11	B	6.10E-09	645000	11	2	0	58636	-	0.00%	0.00%	0.00%	1.0	8.24E-13	0	14.1	limited by boil-up (35t)	0.0%
PIPES, < 2"	break	200	9.14E-12	B	1.83E-09	645000	27	2	0	23540	-	0.00%	0.00%	0.00%	1.0	2.47E-13	0	5.6	limited by boil-up (35t)	0.0%
PIPES, > 2"	leak, small	60	3.05E-10	B	1.83E-08	645000	1	2	0	645000	-	0.00%	0.00%	0.00%	1.0	2.47E-12	0	154.8	exceeds credible time with 0% ventilation	0.0%
PIPES, > 2"	leak, large	60	3.05E-11	B	1.83E-09	645000	27	2	0	23540	-	0.00%	0.00%	0.00%	1.0	2.47E-13	0	5.6	limited by boil-up (35t)	0.0%
PIPES, > 2"	break	60	9.14E-12	B	5.48E-10	645000	27	2	0	23540	-	0.00%	0.00%	0.00%	1.0	7.40E-14	0	5.6	limited by boil-up (35t)	0.0%
Flanges	leak	12	4.00E-07	B	4.80E-06	1000	11	2	0	91	-	20.65%	0.00%	20.65%	0	0	0	-		0.0%
Flanges	break	12	1.00E-09	B	1.20E-08	645000	23	2	0	28043	-	0.00%	0.00%	0.00%	1.0	1.62E-12	0	6.7	0	0.0%

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 0=fail 0 1=fail 1 2=fail 2 (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	PC4 Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes	
VALVE	leak	12	1.00E-08	A	1.20E-07	645000	1	2	0	645000	-	0.00%	0.00%	0.00%	1.0	1.62E-11	0	154.8	exceeds credible time with 0% ventilation	0.1%
																				0.0%
Sample Tubing w/ 100% vent.																				0.0%
Small Dia. Tubing	leak, small	300	3.05E-10	B	9.15E-08	41850	200	0	6000	209	20.30%	-	20.30%	20.30%	0	0	0	-		0.0%
Small Dia. Tubing	leak, large	300	3.05E-10	B	9.15E-08	41850	200	0	6000	209	20.30%	-	20.30%	20.30%	0	0	0	-		0.0%
Small Dia. Tubing	break	300	3.05E-10	B	9.15E-08	41850	200	0	6000	209	20.30%	-	20.30%	20.30%	0	0	0	-		0.0%
																				0.0%
Sample Tubing w/ 50% vent																				0.0%
Small Dia. Tubing	leak, small	300	3.05E-10	B	9.15E-08	41850	200	1	3000	209	19.60%	-	19.60%	19.60%	0	0	0	-		0.0%
Small Dia. Tubing	leak, large	300	3.05E-10	B	9.15E-08	41850	200	1	3000	209	19.60%	-	19.60%	19.60%	0	0	0	-		0.0%
Small Dia. Tubing	break	300	3.05E-10	B	9.15E-08	41850	200	1	3000	209	19.60%	-	19.60%	19.60%	0	0	0	-		0.0%
																				0.0%
Sample Tubing w/ 0% vent.																				0.0%
Small Dia. Tubing	leak, small	300	3.05E-10	B	9.15E-08	41850	200	2	0	209	-	0	0.00%	10.48%	0	0	0	0.8		0.0%
Small Dia. Tubing	leak, large	300	3.05E-10	B	9.15E-08	41850	200	2	0	209	-	0	0.00%	10.48%	0	0	0	0.8		0.0%
Small Dia. Tubing	break	300	3.05E-10	B	9.15E-08	41850	200	2	0	209	-	0	0.00%	10.48%	0	0	0	0.8		0.0%
																				0.0%

PC4		
	Total Fatality Rate:	**2.567E-08**
	Overall ODH Class:	**0**

Yellow hightlight on release rates greater than total ventilation exhaust - for reference

Yellow hightlight on ODH Class if greater than Class 0

SOURCES

A FESHM Chapter 5064, rev. 06/2012
B Risk Analysis for Process Plant, Pipelines and Transport, 1994.
C Guidelines for Process Equipment Reliability Data, with Data Tables, CCPS, 1989
D Source C and B are combined to provide a conservative failure rate and reasonable difference between failure risk and leak risk.

E Vendor data.
F "Consequences of LNG Marine Incidents", Pitblado, et al, CCPS International Conference, 2004.
G Calculated from source A and F data.

NOTES

1 Piping failure rate data is FESHM 5064 convert to a per ft per hour basis.
2 Small leak and break risk for 2" to 6" is same as for less 2".
3 cryostat relief vents outside
4 HRA - Human Reliability Assessment

APPENDIX - ODH TABLE NOTES

Columns (A) through (H) and (T) are user entered.

Column (I) is user entered ventilation flag that indicates whether a row is to be treated as having or not having ventilation.

(A) Equipment - Cryogen containing equipment and general item of failure.

(B) Failure Type – Failure type for specific general item identified under equipment (A). For example, equipment can be "Tank" and failure type can be leak and failure. Each having a different failure rate and consequence.

(C) Number of items – This refers to the number of that Equipment type with the scenario identified on this line.

(D) Individual Failure Rate – This is the failure rate for an individual equipment item having the failure type noted. This is in units of 1/hr.

(E) Source – Here one of the footnote letters is listed to identify the source of the failure rate data.

(F) Total Failure Rate for Item – This is the calculated total failure rate which is the number of items times the individual failure rate. The resulting value is in units of 1/hr.

$$F27 = C27 \cdot D27$$

(G) Available Cryogen Volume – If a value is entered here then the cryogen volume will be used to check the O2 concentration at the point of empty and the time to ODH condition is calculated. The units are cubic feet.

(H) Leak Rate into people space – This is the leak rate for the cryogen release scenario represented in that row. The units are standard cubic feet per minute. Leak rate is also referred to as R.

(I) Vent Failure – This is a flag used to indicate if 0, 1 or 2 ventilation fans failure is assumed. For each release scenario there should be a 1 fan failed and 2 fan failed case so that 100%, 50% and 0% ventilation are represented in the overall fatality rate.

(J) Q – This is the ventilation flow that will be used in determining the impact on O2 concentration. This field is automatically filled depending on if 1 or 2 (both) ODH fans failed in (I). If vent failed=1 then Q is set to Q-Fan1 and if vent failed=2 then Q is set to Q-Fan1-Fan2. Fan 2 is set to be equal to Fan 1 in the top of table.

J27 = IF ($I27="" , "V?" , CHOOSE(($I27+1) , Q , (Q-ODH_Fan1) , (Q-ODH_Fan1-ODH_Fan2)))

(K) Time to Empty – Time to empty the cryogen reservoir will be calculated if an available cryogen volume was entered and the ventilation rate is greater than 0. If the conditions are not met then the Time to Empty is not meaningful and it is set to zero.

$$K27 = \mathrm{IF}\left[\mathrm{AND}(\$G27 > 0\ ,\ \$H27 > 0)\ ,\ \frac{\$G27}{\$H27}\ ,\ 0\right]$$

(L) C(O2) at Empty when Q>R – Concentration of O2 in the space when the cryogen source leaks down to empty. This is only calculated when the ventilation Q (J) is greater than the leak rate (H) and a Time to Empty (K) is greater than zero. The C(O2) formula is specific for when the ventilation is greater than the leak rate.

$$L27 = \mathrm{IF}\left[\mathrm{AND}(\$J27 > \$H27\ ,\ \$K27 > 0)\ ,\ 0.21 \cdot \left(1 - \frac{H27}{\$J27}\right) + \left[0.21 - 0.21 \cdot \left(1 - \frac{\$H27}{\$J27}\right)\right] \cdot e^{\left[-\left(\frac{\$J27}{V}\right) \cdot \$K27\right]}\ ,\ \text{"\_"}\right]$$

(M) C(O2) at Empty when Q<R – Concentration of O2 in the space when the cryogen source leaks down to empty. This is only calculated when the ventilation Q (J) is less than the leak rate, R (H) or Q is zero along with the time to empty being greater than zero. The C(O2) formula is specific for the situation when the ventilation is less than the leak rate.

$$M27 = IF\left[AND(OR(\$J27 < \$H27\ ,\ \$J27 = 0)\ ,\ \$K27 > 0)\ ,\ 0.21 \cdot e^{\left[-\left[\frac{\$H27}{V}\right] \cdot \$K27\right]}\ ,\ \text{"-"}\right]$$

(N) C(O2) at infinity (infinity supply) – Concentration of O2 in the space assuming an infinite supply of cryogen, calculated at time = infinity. C(O2) is calculated by formula when the leak rate is less than the ventilation, R<Q, otherwise C(02) is assumed to reach 0%.

$$N27 = IF\left[\$H27 < \$J27\ ,\ \left[0.21 \cdot \left[1 - \frac{\$H27}{\$J27}\right]\right]\ ,\ IF\ (\$H27 = 0\ ,\ 0.21\ ,\ 0)\right]$$

(O) C(O2) for fatality rate – The maximum C(O2) of the three possible cases is used, C(O2) at empty for Q>R (L), C(O2) at empty for Q<R (M) or C(02) at infinity time. This way a realistic C(O2) is used for subsequent fatality rate calculations.

$$O27 = MAX(\$L27 : \$N27\ )$$

(P) Fatality factor – This is the fatality factor for that line item (scenario).
The slope and b intercept are for a straight line fit between F=0 and F=1.
@ sea level , F=0 at 18%, F=1 at 8.8%, slope = -76.08696 and b=6.695652

$$P27 = IF\left[\$O27 > F\_0\ ,0,\left[IF\left[\$O27 <= F\_1\ ,\ 1,\ 10^{(slope\cdot O27\ +\ b\_intercept)}\right]\right]\right]$$

(Q) Fatality Rate – This is the location specific fatality rate for the line item (scenario). It is calculated at 1-fatality factor for that line item (scenario). The factor is calculated only of the Time to Reach ODH Condition (S) is less than the maximum credible time wthout ventilation, listed above the table. The Fatality Rate is calculated using the probability of full ventilation, probability of 50% ventilation or probability of 0% ventilation based on the ventilation flag (I). The ventilation flag (I) can only have a value of 0, 1 or 2 fans failed.

Q27 = CHOOSE(($I27+1) , ($F27*$P27*P_full_vent) , ($F27*$P27*P_50_Vent_Fail) , ($F27*$P27*p_100_Vent_Fail))

(R) ODH Class* – This is the ODH Class for the line item (scenario). ODH 0, 1, or 2 will be indicated. If ODH 2 is exceeded then it will say "RE-DESIGN". The overall ODH Class is listed at the bottom of the table.

R27 = IF ($Q27 <= 0.0000001 , 0 , IF ($Q27 <= 0.00001 , 1 , IF ($Q27 <= 0.001 , 2 , "RE-DESIGN")))

(S) Time to reach ODH condition – This is the time it will take ODH Class for the line item (scenario). The units are hours.

$$S27 = IF\left[\$O27 <= F\_0\ ,\ IF\left[\$J27 > \$H27\ ,\ \frac{\left[\frac{-V}{\$J27}\right]\cdot LN\left[\frac{\frac{F\_0 - 0.21\cdot\left[1-\frac{\$H27}{\$J27}\right]}{0.21}\cdot\$H27}{\$J27}\right]}{60}\ ,\ \frac{\frac{-V}{\$H27}\cdot LN\left[\frac{F\_0}{0.21}\right]}{60}\right],\text{"\_"}\right]$$

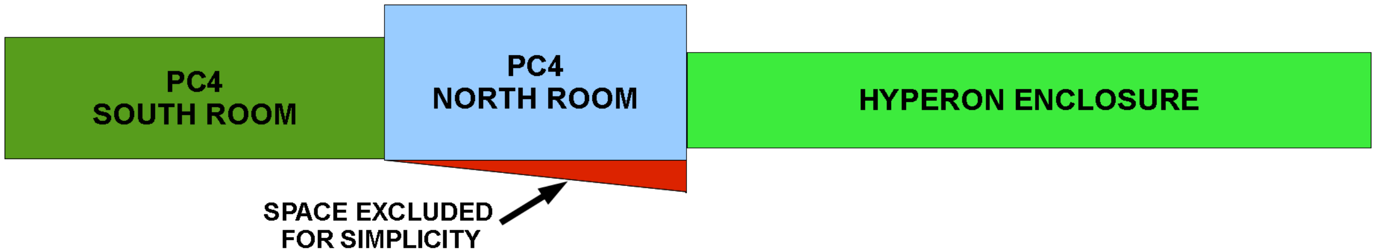
APPENDIX CONTENTS

rev. 12-05-12

PC4 Volume

PC4 (P Central in original drawings) is comprised of 3 distinct sections, with no partitions or walls separating the sections.

The two large rooms are shown. The hyperon beam enclosure is a straight section attached to the North room as indicated.



Height (for ODH Analysis)

$H := 6 \cdot ft = 1.83\,m$

Heavier than air gases are used so only the floor to 6 ft, people space is used for the ODH analysis.

South Section

$L_S := 100 \cdot ft = 30.48 \cdot m$ $\quad W_S := 28 \cdot ft = 8.53\,m$

$V_{south} := L_S \cdot W_S \cdot H$ $\quad V_{south} = 16800 \cdot ft^3$ $\quad V_{south} = 475.72 \cdot m^3$

North Section

$L_N := 80.5 \cdot ft = 24.54\,m$ $\quad W_N := 43 \cdot ft = 13.11\,m$

$V_{north} := L_N \cdot W_N \cdot H$ $\quad V_{north} = 20769 \cdot ft^3$ $\quad V_{north} = 588.11\,m^3$

Hyperon Enclosure

$L_H := 180 \cdot ft = 54.86\,m$ $\quad W_H := 21 \cdot ft = 6.4\,m$

$V_{hyperon} := L_H \cdot W_H \cdot H$ $\quad V_{hyperon} = 22680 \cdot ft^3$ $\quad V_{hyperon} = 642.23\,m^3$

Total PC4 Volume

This is the volume used for the ODH assessment.

$V_{PC4} := V_{south} + V_{north} + V_{hyperon}$ $\quad V_{PC4} = 60249 \cdot ft^3$ $\quad V_{PC4} = 1706.06\,m^3$

PC4 Room dimension data from Drawing 8-4-4-PS-2, Rev A/B, Jan 4, 1974, Titled Proton Laboratory Phase G.

APPENDIX

Cryogen Inventories

Cryogen Data

Argon physical properties from NIST REFPROP

Argon Liquid Density @ 1 psig sat.

$$Ldens_{Ar} := 1391.5 \cdot \frac{kg}{m^3}$$

Argon Gas Density @ 15 C, atm

$$Vdens_{Ar.STD} := 1.6908 \cdot \frac{kg}{m^3}$$

N2 Liquid Density @ 10 psig sat.

$$Ldens_{N2} := 784.34 \cdot \frac{kg}{m^3}$$

N2 Gas Density @ 15 C, atm

$$Vdens_{N2.STD} := 1.1851 \cdot \frac{kg}{m^3}$$

35T cryostat

$$\frac{29.16 \cdot m^3 \cdot Ldens_{Ar}}{Vdens_{Ar.STD}} = 847488 \cdot ft^3$$

$$29.16 \cdot m^3 = 7703.26 \cdot gal$$

LAPD Tank

$$\frac{\pi \cdot \left(\frac{10 \cdot ft}{2}\right)^2 \cdot 10 \cdot ft \cdot Ldens_{Ar}}{Vdens_{Ar.STD}} = 646369 \cdot ft^3$$

$\pi \cdot ($

Filter Vessel

$$\frac{77 \cdot L \cdot Ldens_{Ar}}{Vdens_{Ar.STD}} = 2238 \cdot ft^3$$

Purity Monitor

Filter vessel volume will be used as a high side estimate of purity monitor volume, ignoring filter media.

$77 \cdot L$

Argon Condenser (35T or LAPD)

$$\frac{\pi \cdot \left(\frac{12 \cdot in}{2}\right)^2 \cdot 20 \cdot in \cdot Ldens_{Ar}}{Vdens_{Ar.STD}} = 1077 \cdot ft^3$$

Argon Gas Dewars

$$\frac{8 \cdot 180 \cdot L \cdot Ldens_{Ar}}{Vdens_{Ar.STD}} = 41851 \cdot ft^3$$

LN2 Phase Separator (35T or LAPD)

$$\frac{\pi \cdot \left(\frac{12 \cdot in}{2}\right)^2 \cdot 60 \cdot in \cdot Ldens_{N2}}{Vdens_{N2.STD}} = 2599 \cdot ft^3$$

Failure Rate Date for Evaluating ODH Ventilation Failure

FAN AND ELECTRICAL FAILURE RATE DATA

Electrical Power Failure

$P_{F.elec.pow} := 10^{-4}$ per hr

Fuse - Premature Open

$P_{fuse.p\_open} := 10^{-6}$ per hr

Electric Motor - Failure to Run - Normal Envir.

$P_{F.elec.mot.norm} := 10^{-5}$ per hr

FESHM 5064 motor failure rate is used as the fan failure rate.

ODH Monitoring System Failure

An MSA Ultima XE/XL oxygen monitor with an MSA Gasguard XL control panel or equivalent is assumed for the ODH Monitoring system. Equivalent in this case is a failure rate that is equal to or less than the MSA unit.

The sum of all IEC 61508 failures including non-dangerous failures are used for the oxygen monitor. Ref: Exida certificate MSA 080314 C001, p2.

For the control panel, the total EN 50402 failures is used.
Ref: Physical Technical Testing Institute, certificate FTZU 07 ATEX 0066X,Sup.3, p2.

$P_{F.ODH.mon} := (201 + 4965 + 458) \cdot 10^{-9} = 5.62 \times 10^{-6}$ per hr

$P_{F.ODH.panel} := 29786 \cdot 10^{-9} = 2.98 \times 10^{-5}$ per hr

ODH Ventilation Failure Rates

There are 2 ODH exhaust fans of equal capacity. Each fan has its own floor level intake and exhaust duct routed outside.

ODH fan failure rate (per fan)

A single ODH fan fails **IF**
that fan fails once running **OR**
a fuse fails.

The single fan failure rate is used in the 50% and 100% ventilation failure rate

$P_{F.fan} := P_{F.elec.mot.norm} + P_{fuse.p\_open}$ $\quad P_{F.fan} = 1.1 \times 10^{-5}$ per hr

ODH 50% ventilation rate

The ODH ventilation will be at 50% if one of the fans fails.

The ODH ventilation is 50% **IF**
fan 1 fails **OR** fan 2 fails.

$P_{F.fan} + P_{F.fan} = 2.2 \times 10^{-5}$ per hr

ODH 100% ventilation failure rate

The ODH ventilation would be 0% (total failure) **IF**
power fails **OR**
the ODH monitor fails **OR**
the ODH control panel fails **OR**
fan 1 **AND** fan 2 fail.

$P_{F.elec.pow} + P_{F.ODH.mon} + P_{F.ODH.panel} + \left(P_{F.fan} \cdot P_{F.fan}\right) = 1.35 \times 10^{-4}$ per hr

APPENDIX

Membrane Cryostat Leak Failure Rate

The membrane tank technology used in the LNG industry has not suffer a significant failure since membrane tanks technology was first developed and tested by DNV Research and sold to a French company in 1962.

IHI provided failure rate data based on Quantitative Risk Analysis (QRA). A QRA for KOGAS (GTT technology) is also available. The two QRA's are compared to arrive at a conservative membrane leak failure rate that can be used evaluating ODH for either IHI or GTT membranes.

Both QRA's include dropped pump as a failure source. For removable pumps in LAr, the dropped pump scenario should be evaluated and detailed as a separate line item in the ODH.

The 35T cryostat does not have a removable pump and is not subject to the dropped pump risk.

IHI above ground membrane tank - internal Leak Failure Rate

$$\frac{140-(138-95)}{1\cdot 10^{6}\cdot \mathrm{yr}} = 1.11\times 10^{-8}\cdot\frac{1}{\mathrm{hr}}$$

This is the published IHI failure rate, 140 with the pump drop contribution (138-95) subtracted out.

ref: PC Membrane Tank Brochure from IHI.

KOGAS above ground membrane tank - internal leak failure Rate

$$1.33\times 10^{-4}\cdot\frac{1}{\mathrm{yr}} - \frac{30}{1\times 10^{6}\cdot \mathrm{yr}} = 1.18\times 10^{-8}\cdot\frac{1}{\mathrm{hr}}$$

(excluding pump drop)

Internal leak failure rate includes failures due to outer concrete failures.

ref: Safety Comparison of LNG Tank Designs with Fault Tree Analysis, presented at 23rd World Gas Conference, 2006

The IHI and KOGAS internal leak failure rates are of the same magnitude and differ by less than 10%. The more conservative KOGAS number will be used.

APPENDIX

Membrane Cryostat Major Failure Rate

IHI and KOGAS provide external leak failure data which is the failure of the membrane and containment barrier.

IHI above ground membrane tank - external Leak Failure Rate

$$\frac{38-(31)}{1\cdot 10^{6}\cdot \mathrm{yr}} = 7.99\times 10^{-10}\cdot\frac{1}{\mathrm{hr}}$$

This is the published IHI failure rate, 38 with the pump drop contribution (31) subtracted out.

ref: PC Membrane Tank Brochure from IHI.

KOGAS above ground membrane tank - external leak failure Rate

$$(3.47-3)10^{-6}\cdot\frac{1}{\mathrm{yr}} = 5.36\times 10^{-11}\cdot\frac{1}{\mathrm{hr}}$$

External leak failure rate includes failures due to outer concrete failures.

ref: Safety Comparison of LNG Tank Designs with Fault Tree Analysis, presented at 23rd World Gas Conference, 2006

The more conservative IHI external leak failure rates will be used.

Pipe Leaks and Breaks - Argon Pumped Loop

The calculations that follow, determine the liquid argon piping leak rate for a small leak (10 mm^2), a large leak (500mm^2, average) and a pipe break. The leak rate calculations are performed as flow across an orifice of the leak or pipe size. The maximum pump pressure is used as the source pressure.

The maximum credible flowrate is highest for the initial piping and then decreases with additional piping and fittings. To account for this reality, a credible maximum flowrate is determined at the halfway point of the argon loop. This is then applied to the whole loop.

$Area_{S.leak} := 10 \cdot mm^2 = 0.0155 \cdot in^2$

$Area_{L.leak} := 500 \cdot mm^2 = 0.775 \cdot in^2$

Average large leak size will be used for the calcs.

Argon Data

Argon physical properties from NIST REFPROP

Argon Liquid Density

$Ldens_{Ar} = 1391.5 \cdot \frac{kg}{m^3}$

Argon Gas Density @ standard conditions

$Vdens_{Ar.STD} = 1.6908 \cdot \frac{kg}{m^3}$

$Vdens_{Ar.cold} := 6.85 \cdot \frac{kg}{m^3}$ saturated @ 3 psig

Argon liquid visc

$\mu_{ArL} := 0.25 \cdot cP$

Pipe ID - 1" sched 10

$Pipe_{ID} := 1.097 \cdot in$

$$Area_{pipe} := \pi \cdot \left(\frac{Pipe_{ID}}{2}\right)^2 = 0.945 \cdot in^2$$

Orifice Flow Coefficient (square edged orifice)

$C := 0.62$

Available Pressure into piping @ floor level (tank Pres + tank liquid head+ pump head)

ref:35t Pump, ACD technical data, dated 08/26/11

$$Pipe_{in} := \left[3 \cdot psi + \left(10ft \cdot g \cdot Ldens_{Ar}\right) + \left(90ft \cdot g \cdot Ldens_{Ar}\right)\right] - 0 \cdot psi$$

$Pipe_{in} = 63.35 \cdot psi$

APPENDIX

Piping Equiv. Length:

$$L_{pipe} := \frac{200 \cdot ft + 25 \cdot ft + 60 \cdot ft}{2}$$

$$L_{pipe} = 142.5 \cdot ft$$

200 ft of straight pipe to/from filter skid, 25 ft of pipe within the skid and 60 equiv. feet for minor fittings such as elbows. Valves handled below.

Friction Factor Guess

$f := 0.02$

Pipe Roughness:

$\varepsilon := 0.0005 \cdot ft$

Pump maximum flow

$pump_{flow.max} := 30 \cdot gpm$

Given

Darcy's Friction Factor:

$$\frac{1}{\sqrt{f}} = -2.0 \cdot \log\left(\frac{\varepsilon}{3.7 \cdot Pipe_{ID}} + \frac{2.51}{4 \cdot \frac{pump_{flow.max} \cdot Ldens_{Ar}}{Pipe_{ID} \cdot \pi \cdot \mu_{ArL}} \cdot \sqrt{f}}\right)$$

$f_{pipe} := Find(f)$ $\qquad$ $f_{pipe} = 0.0314$

Full open valve Cv's

$$Cv_{globeV} := \frac{18 \cdot gpm}{\sqrt{psi}} \qquad Cv_{slantV} := \frac{27 \cdot gpm}{\sqrt{psi}}$$

The slant valve is also referred to as a "Y" valve.

Units from basic Cv definition added to allow Mathcad to handle unit conversions. Cv definition listed at end of appendix, for reference.

Number of valves in the flow path to piping midpoint

$Num_{globeV} := 5 \qquad Num_{slantV} := 1$

Water Density (for SG calc)

$$\rho_{H2O.60F} := 62.37 \cdot \frac{lb}{ft^3}$$

LAr specific gravity

$$SG_{LAr} := \frac{Ldens_{Ar}}{\rho_{H2O.60F}}$$

Guesses to seed the solver (on next page)

$max_{credible.Lflow} := 50 \cdot gpm \qquad \Delta P_{pipe} := 2 \cdot psi$

$fluid_{vel} := 5 \cdot \frac{ft}{min} \qquad \Delta P_{valves} := 2 \cdot psi$

APPENDIX

Given

$$\Delta P_{valves} = Num_{globeV} \cdot SG_{LAr} \cdot \left(\frac{max_{credible.Lflow}}{Cv_{globeV}} \right)^2 + Num_{slantV} \cdot SG_{LAr} \cdot \left(\frac{max_{credible.Lflo}}{Cv_{slantV}} \right.$$

$$fluid_{vel} = \frac{max_{credible.Lflow}}{Area_{pipe}} \qquad \Delta P_{pipe} = f_{pipe} \cdot Ldens_{Ar} \cdot \frac{L_{pipe}}{Pipe_{ID}} \cdot \frac{(fluid_{vel})^2}{2}$$

$$Pipe_{in} - \Delta P_{pipe} - \Delta P_{valves} = 0$$

$$\begin{pmatrix} max_{credible.Lflow} \\ \Delta P_{pipe} \\ \Delta P_{valves} \\ fluid_{vel} \end{pmatrix} := Find(max_{credible.Lflow}, \Delta P_{pipe}, \Delta P_{valves}, fluid_{vel})$$

$$max_{credible.Lflow} = 28.82 \cdot gpm$$

$$\Delta P_{pipe} = 43.9 \cdot psi \qquad \Delta P_{valves} = 19.4 \cdot psi \qquad fluid_{vel} = 9.78 \cdot \frac{ft}{sec}$$

$$max_{Gflow} := max_{credible.Lflow} \cdot \frac{Ldens_{Ar}}{Vdens_{Ar.STD}} \qquad max_{Gflow} = 3170 \cdot \frac{ft^3}{min}$$

The filter vessels and purity monitor are downstream of the midpoint. The above max flow is also the max leak flow rate for a catastrophic vessel failure of the filters or purity monitor.

Available pressure across orifice

$\Delta P := Pipe_{in}$ The maximum pressure is used (piping inlet pressure)

Flow from Pipe Break - Argon Pumped Loop

$$Leak_{Ar.brk} := \frac{\left(C \cdot Area_{pipe} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Ldens_{Ar}}} \cdot Ldens_{Ar}\right)}{Vdens_{Ar.STD}}$$

$$Leak_{Ar.brk} = 467.8 \cdot \frac{m^3}{min}$$

$$Leak_{Ar.brk} = 16521 \cdot \frac{ft^3}{min}$$

This exceeds the maximum credible flow rate, the maximum credible flow will be used in the ODH assessment table.

For ref:

$$max_{Gflow} = 3170 \cdot \frac{ft^3}{min}$$

Flow from Small Leak - Argon Pumped Loop

$$\frac{\left(C \cdot Area_{S.leak} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Ldens_{Ar}}} \cdot Ldens_{Ar}\right)}{Vdens_{Ar.STD}} = 271 \cdot \frac{ft^3}{min}$$

Flow from Large Leak - Argon Pumped Loop

$$\frac{\left(C \cdot Area_{L.leak} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Ldens_{Ar}}} \cdot Ldens_{Ar}\right)}{Vdens_{Ar.STD}} = 13546 \cdot \frac{ft^3}{min}$$

For ref:

$$max_{Gflow} = 3170 \cdot \frac{ft^3}{min}$$

This exceeds the maximum credible flow rate, the maximum credible flow will be used in the ODH assessment table.

APPENDIX

Flow from Small Flange Leak - Argon

$$\frac{\left(C\cdot Area_{S.leak}\cdot\sqrt{2\cdot g\cdot\frac{\Delta P\cdot 1\frac{lbm}{lbf}}{Ldens_{Ar}}}\cdot Ldens_{Ar}\right)}{Vdens_{Ar.STD}} = 271\cdot\frac{ft^3}{min}$$

The small leak area is taken as the same as for a small pipe leak.

Flow from Flange Break - Argon

Assuming that 100% of pipe ID becomes a leak with a 2 mm gap.

$$Area_{flg.break} := 100\%\cdot(2\pi\cdot Pipe_{ID})\cdot 2\cdot mm = 0.54273\cdot in^2$$

$$\frac{\left(C\cdot Area_{flg.break}\cdot\sqrt{2\cdot g\cdot\frac{\Delta P\cdot 1\frac{lbm}{lbf}}{Ldens_{Ar}}}\cdot Ldens_{Ar}\right)}{Vdens_{Ar.STD}} = 9486\cdot\frac{ft^3}{min}$$

For ref:

$$max_{Gflow} = 3170\cdot\frac{ft^3}{min}$$

This exceeds the maximum credible flow rate, the maximum credible flow will be used in the ODH assessment table.

$$LAPD_{pump.limit} := 3500\cdot\frac{L}{hr}\cdot\frac{Ldens_{Ar}}{Vdens_{Ar.STD}}$$

ref: BNCP-32B Liquid Argon Pump Curve, LARTPC DOC 474-v1.

$$LAPD_{pump.limit} = 1695\cdot\frac{ft^3}{min}$$

Per pump vendor pump flow will not exceed 3500 LPH. Pump performance drops off rapidly moving to right on the pump curve.

The LAPD max pump flow only applies to the LAPD pump. The 35t pumps are submerged inside the cryostat and do not leak into the people space.

LAPD Tank Leaks

LAPD Tank Small Leak - Static head only

$$\frac{\left[C \cdot Area_{S.leak} \cdot \sqrt{2 \cdot g \cdot \frac{(10ft \cdot g \cdot Ldens_{Ar}) \cdot 1 \frac{lbm}{lbf}}{Ldens_{Ar}} \cdot Ldens_{Ar}}\right]}{Vdens_{Ar.STD}} = 84 \cdot \frac{ft^3}{min}$$

LAPD Tank catastrophic failure is taken as breaking the largest below liquid nozzle

$$LAPD_{nozzle.brk} := \frac{\left[C \cdot \left[\pi \cdot \left(\frac{2.067 \cdot in}{2}\right)^2\right] \cdot \sqrt{2 \cdot g \cdot \frac{(10ft \cdot g \cdot Ldens_{Ar}) \cdot 1 \frac{lbm}{lbf}}{Ldens_{Ar}} \cdot Ldens_{Ar}}\right]}{Vdens_{Ar.STD}}$$

$$LAPD_{nozzle.brk} = 18103 \cdot \frac{ft^3}{min}$$

Argon Heat of Vap.

$$Hvap_{Ar} := 160 \cdot \frac{kJ}{kg}$$

LAPD tank max boilup rate

$$Boilup_{max.LAPD} := \frac{2.4 \cdot kW}{Hvap_{Ar}} \qquad Boilup_{max.LAPD} = 0.9 \cdot \frac{kg}{min}$$

$$Boilup_{Gmax.LAPD} := \frac{Boilup_{max.LAPD}}{Vdens_{Ar.STD}} \qquad Boilup_{Gmax.LAPD} = 18.8 \cdot \frac{ft^3}{min}$$

35t Cryostat Leaks

35T catastrophic failure is taken as 1 mm by 0.33 m flow path through all containment

$$C35T_{largeleak} := \frac{\left[C\cdot(1\cdot mm\cdot 0.33\cdot m)\cdot\sqrt{2\cdot g\cdot\frac{(2700\cdot mm\cdot g\cdot Ldens_{Ar})\cdot 1\frac{lbm}{lbf}}{Ldens_{Ar}}}\cdot Ldens_{Ar}\right]}{Vdens_{Ar.STD}}$$

$$C35T_{largeleak} = 2597\cdot\frac{ft^3}{min}$$

35t Cryostat max boilup rate

$$Boilup_{max.35t} := \frac{3.5\cdot kW}{Hvap_{Ar}} \qquad Boilup_{max.35t} = 1.3\cdot\frac{kg}{min}$$

$$Boilup_{Gmax.35t} := \frac{Boilup_{max.35t}}{Vdens_{Ar.STD}} \qquad Boilup_{Gmax.35t} = 27.4\cdot\frac{ft^3}{min}$$

Max boilup rate for vent pipe leak calcs

The larger 35t max boilup is used for the vent piping leak calculations.

$$Boilup_{Gmax.35t} = 27.4\cdot\frac{ft^3}{min}$$

APPENDIX

Pipe Leaks and Breaks - Argon Vent Pipe

This calculation determines the Argon leak rate for a small leak (10 mm^2), a large leak (500 mm^2, average) and a pipe break. The available pressure for vents pipes is 3 psig or less. The calculations are performed as flow across an orifice of the leak or pipe size.

The LAPD maximum boilup rate is used to calculate a worst case maximum vent pipe back pressure. This pressure is then used for the argon vent pipe leak calcs (applied to 35t and LAPD).

Pipe ID - 3" sched 10

$Pipe_{ID} := 3.26 \cdot in$

$$Area_{pipe} := \pi \cdot \left(\frac{Pipe_{ID}}{2}\right)^2 = 8.347 \cdot in^2$$

Equivalent Pipe Length:

$L := 200 \cdot ft$

Pipe Roughness:

$\varepsilon = 0.0005 \cdot ft$

Friction Factor

$f := 0.002$

Density of GAr @ 300 K & atm

$$\rho_{gas.warm} := 1.6238 \cdot \frac{kg}{m^3}$$

Viscosity of GAr @ 300 K & atm

$\mu_{warm} := 0.022741 \cdot cP$

Given

Darcy's Friction Factor:

$$\frac{1}{\sqrt{f}} = -2.0 \cdot \log\left(\frac{\varepsilon}{3.7 \cdot Pipe_{ID}} + \frac{2.51}{4 \cdot \frac{Boilup_{max.LAPD}}{Pipe_{ID} \cdot \pi \cdot \mu_{warm}} \cdot \sqrt{f}}\right)$$

Cranes used Darcy's friction factor.

$f_{pipe} := Find(f)$ $\qquad f_{pipe} = 0.03347$

$$vel_{outlet} := \frac{\frac{Boilup_{max.LAPD}}{\rho_{gas.warm}}}{\pi \cdot \left(\frac{Pipe_{ID}}{2}\right)^2}$$

$vel_{outlet} = 1.7 \cdot \frac{m}{s}$ $\qquad vel_{outlet} = 5.6 \cdot \frac{ft}{s}$

$$P_{outlet.backP} := \rho_{gas.warm} \cdot f_{pipe} \cdot \frac{L}{Pipe_{ID}} \cdot \frac{vel_{outlet}^2}{2}$$

$P_{outlet.backP} = 0.009 \cdot psi$

This is the maximum vent pipe backpressure which is also the maximum source pressure for a vent pipe leak.

APPENDIX

Available Pressure - Across Orifice

$\Delta P := \left(P_{outlet.backP}\right) - 0 \cdot psi$ $\qquad \Delta P = 0.009 \cdot psi$

Pipe ID - 3" sched 10

$Pipe_{ID} := 3.26 \cdot in$

$$Area_{pipe} := \pi \cdot \left(\frac{Pipe_{ID}}{2}\right)^2 = 8.347 \cdot in^2$$

Flow from Pipe Break - Argon Vent Pipe

for ref.

$$Boilup_{Gmax.LAPD} = 18.80 \cdot \frac{ft^3}{min}$$

$$\frac{\left(C \cdot Area_{pipe} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Vdens_{Ar.cold}} } \cdot Vdens_{Ar.cold}\right)}{Vdens_{Ar.STD}} = 118.9 \cdot \frac{ft^3}{min}$$

$$Boilup_{Gmax.35t} = 27.4 \cdot \frac{ft^3}{min}$$

This exceeds the max boilup rate so the max boilup rate will be used in the ODH tabulation.

Flow from Small Leak - Argon Vent Pipe

$$\frac{\left(C \cdot Area_{S.leak} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Vdens_{Ar.cold}} } \cdot Vdens_{Ar.cold}\right)}{Vdens_{Ar.STD}} = 0.22 \cdot \frac{ft^3}{min}$$

Flow from Large Leak - Argon Vent Pipe

$$\frac{\left(C \cdot Area_{L.leak} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Vdens_{Ar.cold}}} \cdot Vdens_{Ar.cold}\right)}{Vdens_{Ar.STD}} = 11.04 \cdot \frac{ft^3}{min}$$

Flow from Small Flange Leak - Argon Vent Pipe

$$\frac{\left(C \cdot Area_{S.leak} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Vdens_{Ar.cold}}} \cdot Vdens_{Ar.cold}\right)}{Vdens_{Ar.STD}} = 0.22 \cdot \frac{ft^3}{min}$$

The small leak area is taken as the same as for a small pipe leak.

Flow from Flange Break - Argon Vent Pipe

Assuming that 100% of pipe ID becomes a leak with a 2 mm gap.

$$Area_{flg.break} := 100\% \cdot \left(2\pi \cdot Pipe_{ID}\right) \cdot 2 \cdot mm = 1.61285 \cdot in^2$$

$$\frac{\left(C \cdot Area_{flg.break} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Vdens_{Ar.cold}}} \cdot Vdens_{Ar.cold}\right)}{Vdens_{Ar.STD}} = 23.0 \cdot \frac{ft^3}{min}$$

Conflat Leaks and Breaks - Argon Vapor

This calculation determines the Argon leak rate for conflat leaks. Use of conflats is assumed to limited to service that would only see argon gas at cryostat vapor space pressure. The available pressure from the cryostat vapor space is 3 psig or less. The calculations are performed as flow across an orifice of the leak or pipe size.

Available Pressure - Across Orifice

$$\Delta P := (3.0 \cdot psi) - 0 \cdot psi$$

Argon Gas Density (Saturated @ 3 psig)

$$Vdens_{Ar.cold} = 6.85 \cdot \frac{kg}{m^3}$$

Pipe ID - 4" sched 10

$$Pipe_{ID} := 4.260 \cdot in$$

$$Area_{pipe} := \pi \cdot \left(\frac{Pipe_{ID}}{2}\right)^2 = 14.253 \cdot in^2$$

Flow from Small Conflat Leak - Argon Vapor

$$\frac{\left(C \cdot Area_{S.leak} \cdot \sqrt{2 \cdot g \cdot \dfrac{\Delta P \cdot 1 \dfrac{lbm}{lbf}}{Vdens_{Ar.cold}} \cdot Vdens_{Ar.cold}}\right)}{Vdens_{Ar.STD}} = 4 \cdot \frac{ft^3}{min}$$

The small leak area is taken as the same as for a small pipe leak.

Flow from Conflat Break - Argon Vapor

Assuming that 100% of pipe ID becomes a leak with a 1/2 mm gap. The tight fit and knife edge seal reduces the gap potential compared to traditional flanges.

$$Area_{flg.break} := 100\% \cdot (2\pi \cdot Pipe_{ID}) \cdot \frac{1}{2} \cdot mm = 0.5269 \cdot in^2$$

$$\frac{\left(C \cdot Area_{flg.break} \cdot \sqrt{2 \cdot g \cdot \dfrac{\Delta P \cdot 1 \dfrac{lbm}{lbf}}{Vdens_{Ar.cold}} \cdot Vdens_{Ar.cold}}\right)}{Vdens_{Ar.STD}} = 141 \cdot \frac{ft^3}{min}$$

for ref.

$$Boilup_{Gmax.LAPD} = 18.80 \cdot \frac{ft^3}{mir}$$

$$Boilup_{Gmax.35t} = 27.4 \cdot \frac{ft^3}{mir}$$

This exceeds the max boilup rate so the max boilup rate will be used in the ODH tabulation.

Pipe Leaks and Breaks - Liquid Nitrogen

The calculations that follow, determine the liquid nitrogen piping leak rate for a small leak (10 mm^2), a large leak (500mm^2, average) and a pipe break. The leak rate calculations are performed as flow across an orifice of the leak or pipe size. The source pressure is the LN2 trailer outside PC4.

The credible maximum flowrate cannot be higher than the maximum flowrate that can pass through the outdoor portion of supply piping.

N2 Data

Physical properties from NIST REFPROP

N2 Liquid Density

$$Ldens_{N2} := 807 \cdot \frac{kg}{m^3}$$

$$\mu_{N2} := 0.11 \cdot cP$$

N2 Gas Density @ standard conditions

$$Vdens_{N2.STD} := 1.183 \cdot \frac{kg}{m^3}$$

Orifice Flow Coefficient (square edged orifice)

$$C := 0.62$$

Pipe ID - 1", K Copper Tube

$$Pipe_{ID} := 0.995 \cdot in \qquad Area_{pipe} := \pi \cdot \left(\frac{Pipe_{ID}}{2}\right)^2 = 0.778 \cdot in^2$$

$$Area_{S.leak} := 10 \cdot mm^2 = 0.0155 \cdot in^2$$

$$Area_{L.leak} := 500 \cdot mm^2 = 0.775 \cdot in^2$$

Average large leak size will be used for the calcs.

Available Pressure into piping @ lowest piping point (Trailer Pres + pipe liquid head)

$$P_{trailer} := \left(40 \cdot psi + 12ft \cdot g \cdot Ldens_{N2}\right) - 0 \cdot psi$$

$$P_{trailer} = 44.20 \cdot psi$$

APPENDIX

Piping Equiv. Length:

$L := 824in + 12 \cdot ft$

$L = 80.7 \cdot ft$

The outside section of pipe from the LN2 trailer to PC4 is 824 inches with 12 ft for misc elbows.

Friction Factor Guess

$f := 0.02$

Pipe Roughness:

$\varepsilon := 0.0005 \cdot ft$

Given

Darcy's Friction Factor:

$$\frac{1}{\sqrt{f}} = -2.0 \cdot \log\left(\frac{\varepsilon}{3.7 \cdot Pipe_{ID}} + \frac{2.51}{4 \cdot \frac{20 \cdot gpm \cdot Ldens_{N2}}{Pipe_{ID} \cdot \pi \cdot \mu_{N2}} \cdot \sqrt{f}}\right)$$

Arbitrary 20 gpm flow to get turbulent friction factor

$f_{pipe} := Find(f)$ $\qquad f_{pipe} = 0.03235$

Trailer valve, full open valve Cv

$$Cv_{trailerV} := \frac{2 \cdot gpm}{\sqrt{psi}}$$

Units from basic Cv definition added to allow Mathcad to handle unit conversions.
Cv definition listed at end of appendix, for reference.

LN2 specific gravity

$$SG_{LN2} := \frac{Ldens_{N2}}{\rho_{H2O.60F}}$$

Guesses to seed the solver (on next page)

$max_{credible.Lflow} := 50 \cdot gpm$ $\qquad \Delta P_{pipe} := 2 \cdot psi$

$fluid_{vel} := 5 \cdot \frac{ft}{min}$ $\qquad \Delta P_{valve} := 2 \cdot psi$

APPENDIX

Given

$$\Delta P_{valve} = 1 \cdot SG_{LN2} \cdot \left(\frac{max_{credible.Lflow}}{Cv_{trailerV}} \right)^2$$

$$fluid_{vel} = \frac{max_{credible.Lflow}}{Area_{pipe}} \qquad \Delta P_{pipe} = f_{pipe} \cdot Ldens_{N2} \cdot \frac{L}{Pipe_{ID}} \cdot \frac{(fluid_{vel})^2}{2}$$

$$Pipe_{in} - \Delta P_{pipe} - \Delta P_{valves} = 0$$

$$\begin{pmatrix} max_{credible.Lflow} \\ \Delta P_{pipe} \\ \Delta P_{valve} \\ fluid_{vel} \end{pmatrix} := Find(max_{credible.Lflow}, \Delta P_{pipe}, \Delta P_{valve}, fluid_{vel})$$

$$max_{credible.Lflow} = 38.82 \cdot gpm$$

$$\Delta P_{pipe} = 43.9 \cdot psi \qquad \Delta P_{valves} = 19.4 \cdot psi \qquad fluid_{vel} = 16.02 \cdot \frac{ft}{sec}$$

$$max_{Gflow} := max_{credible.Lflow} \cdot \frac{Ldens_{N2}}{Vdens_{N2.STD}} \qquad max_{Gflow} = 3540 \cdot \frac{ft^3}{min}$$

This is the max LN2 flow into PC4. This flow will be used to check the LN2 piping leaks.

There is a later calc that determines how much LN2 can reach the phase separator. That limit is used for the phase separator leak.

APPENDIX

Available pressure across orifice

$$\Delta P := P_{trailer}$$

The inside LN2 piping is 1" copper to LAPD and 1" SS, sched 10 to 35t. The 1" SS will be used in the calcs and applied to all the inside LN2 piping.

Pipe ID - 1" sched 10

$$Pipe_{ID} := 1.097 \cdot in \qquad Area_{pipe} := \pi \cdot \left(\frac{Pipe_{ID}}{2}\right)^2 = 0.945 \cdot in^2$$

Flow from Pipe Break - Liquid Nitrogen

$$\frac{\left(C \cdot Area_{pipe} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Ldens_{N2}}} \cdot Ldens_{N2}\right)}{Vdens_{N2.STD}} = 15020 \cdot \frac{ft^3}{min}$$

For ref:

$$max_{Gflow} = 3540 \cdot \frac{ft^3}{min}$$

This exceeds the maximum credible flow rate, the maximum credible flow will be used in the ODH assessment table.

Flow from Small Leak - Liquid Nitrogen

$$\frac{\left(C \cdot Area_{S.leak} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Ldens_{N2}}} \cdot Ldens_{N2}\right)}{Vdens_{N2.STD}} = 246 \cdot \frac{ft^3}{min}$$

APPENDIX

Flow from Large Leak - Liquid Nitrogen

$$\frac{\left(C\cdot Area_{L.leak}\cdot\sqrt{2\cdot g\cdot\frac{\Delta P\cdot 1\frac{lbm}{lbf}}{Ldens_{N2}}}\cdot Ldens_{N2}\right)}{Vdens_{N2.STD}} = 12316\cdot\frac{ft^3}{min}$$

For ref:

$$max_{Gflow} = 3540\cdot\frac{ft^3}{min}$$

This exceeds the maximum credible flow rate, the maximum credible flow will be used in the ODH assessment table.

Flow from Small Flange Leak - Liquid Nitrogen

$$\frac{\left(C\cdot Area_{S.leak}\cdot\sqrt{2\cdot g\cdot\frac{\Delta P\cdot 1\frac{lbm}{lbf}}{Ldens_{N2}}}\cdot Ldens_{N2}\right)}{Vdens_{N2.STD}} = 246\cdot\frac{ft^3}{min}$$

The small leak area is the same as for a small pipe leak.

Flow from Flange Break - Liquid Nitrogen

Assuming that 100% of pipe ID becomes a leak with a 2 mm gap.

$$Area_{flg.break} := 100\%\cdot\left(2\pi\cdot Pipe_{ID}\right)\cdot 2\cdot mm = 0.54273\cdot in^2$$

$$\frac{\left(C\cdot Area_{flg.break}\cdot\sqrt{2\cdot g\cdot\frac{\Delta P\cdot 1\frac{lbm}{lbf}}{Ldens_{N2}}}\cdot Ldens_{N2}\right)}{Vdens_{N2.STD}} = 8625\cdot\frac{ft^3}{min}$$

For ref:

$$max_{Gflow} = 3540\cdot\frac{ft^3}{min}$$

This exceeds the maximum credible flow rate, the maximum credible flow will be used in the ODH assessment table.

APPENDIX

Pipe Leaks and Breaks - Nitrogen Gas

This calculation determines the Nitrogen leak rate for a small leak (10 mm^2), a large leak (10 mm^2 to 1000 mm^2) and a pipe break. The calculations are performed as flow across an orifice of the leak or pipe size.

N2 Data Physical properties from NIST REFPROP

N2 Vapor Density (saturated @ 5 psig

$$Vdens_{N2} := 6.05 \cdot \frac{kg}{m^3}$$

N2 Gas Density @ standard conditions

$$Vdens_{N2.STD} := 1.183 \cdot \frac{kg}{m^3}$$

The amount of nitrogen gas leaving the condenser is limited by the LN2 supply coming in. The following calculation determines the maximum LN2 that can reach the phase separator. The maximum N2 gas cannot be greater than this value.

Available Pressure into piping @ elevation of phase separator (Trailer Pres + pipe liquid head)

$$P_{phase.sep} := 40 \cdot psi + (144 \cdot in - 96 \cdot in) \cdot g \cdot Ldens_{N2} - 0 \cdot psi$$

$$P_{phase.sep} = 41.40 \cdot psi$$

Pipe ID - 1", K Copper Tube

Here the liquid supply pipe ID is used to determine the max liquid to the phase separator.

$$Pipe_{ID} := 0.995 \cdot in \qquad Area_{pipe} := \pi \cdot \left(\frac{Pipe_{ID}}{2}\right)^2 = 0.778 \cdot in^2$$

Piping Equiv. Length:

$$L := 824in + 12 \cdot ft + 696 \cdot in + 21 \cdot ft$$

$$L = 159.7 \cdot ft$$

The outside section of pipe from the LN2 trailer to PC4 is 824 inches with 12 ft for misc elbows. The inside portion is 696 inches with 21 ft for misc elbows.

Friction Factor Guess

$$f := 0.02$$

Pipe Roughness:

$$\varepsilon := 0.0005 \cdot ft$$

Given

Darcy's Friction Factor:

$$\frac{1}{\sqrt{f}} = -2.0 \cdot \log\left(\frac{\varepsilon}{3.7 \cdot Pipe_{ID}} + \frac{2.51}{4 \cdot \frac{20 \cdot gpm \cdot Ldens_{N2}}{Pipe_{ID} \cdot \pi \cdot \mu_{N2}} \cdot \sqrt{f}}\right)$$

Arbitrary 20 gpm flow to get turbulent friction factor

$$f_{pipe} := Find(f) \qquad f_{pipe} = 0.03235$$

Guesses to seed the solver

$max_{credible.Lflow} := 50 \cdot gpm$

$\Delta P_{pipe} := 2 \cdot psi$

$fluid_{vel} := 5 \cdot \frac{ft}{min}$

$\Delta P_{valve} := 2 \cdot psi$

Given

$$\Delta P_{valve} = 1 \cdot SG_{LN2} \cdot \left(\frac{max_{credible.Lflow}}{Cv_{trailerV}} \right)^2$$

$$fluid_{vel} = \frac{max_{credible.Lflow}}{Area_{pipe}}$$

$$\Delta P_{pipe} = f_{pipe} \cdot Ldens_{N2} \cdot \frac{L}{Pipe_{ID}} \cdot \frac{(fluid_{vel})^2}{2}$$

$$Pipe_{in} - \Delta P_{pipe} - \Delta P_{valves} = 0$$

$$\begin{pmatrix} max_{credible.Lflow} \\ \Delta P_{pipe} \\ \Delta P_{valve} \\ fluid_{vel} \end{pmatrix} := Find(max_{credible.Lflow}, \Delta P_{pipe}, \Delta P_{valve}, fluid_{vel})$$

$max_{credible.Lflow} = 27.60 \cdot gpm$

$\Delta P_{pipe} = 43.9 \cdot psi$ $\quad \Delta P_{valves} = 19.4 \cdot psi$ $\quad fluid_{vel} = 11.39 \cdot \frac{ft}{sec}$

$$max_{Gflow} := max_{credible.Lflow} \cdot \frac{Ldens_{N2}}{Vdens_{N2.STD}}$$

$max_{Gflow} = 2517 \cdot \frac{ft^3}{min}$

This is the maximum possible flow of LN2 to the phase separator . This is the maximum N2 available to vent as nitrogen gas. This maximum also applies to a phase separator failure.

APPENDIX

Available Pressure - Across Orifice

$\Delta P := P_{phase.sep} - 0 \cdot psi$ $\qquad \Delta P = 41.4 \cdot psi$

Orifice Flow Coefficient (square edged orifice)

$C := 0.62$

Pipe ID - 1" sched 10

$Pipe_{ID} := 1.097 \cdot in$ $\qquad Area_{pipe} := \pi \cdot \left(\frac{Pipe_{ID}}{2}\right)^2 = 0.945 \cdot in^2$

Pipe size for GN2 leaving condenser.

Flow from Pipe Break - Nitrogen Gas

$$\frac{\left(C \cdot Area_{pipe} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Vdens_{N2}}} \cdot Vdens_{N2}\right)}{Vdens_{N2.STD}} = 1259 \cdot \frac{ft^3}{min}$$

Flow from Small Leak - Nitrogen Gas

$$\frac{\left(C \cdot Area_{S.leak} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1 \frac{lbm}{lbf}}{Vdens_{N2}}} \cdot Vdens_{N2}\right)}{Vdens_{N2.STD}} = 21 \cdot \frac{ft^3}{min}$$

Flow from Large Leak - Nitrogen Gas

$$\frac{\left(C \cdot Area_{L.leak} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1\frac{lbm}{lbf}}{Vdens_{N2}} \cdot Vdens_{N2}}\right)}{Vdens_{N2.STD}} = 1032 \cdot \frac{ft^3}{min}$$

Flow from Small Flange Leak - Nitrogen Gas

$$\frac{\left(C \cdot Area_{S.leak} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1\frac{lbm}{lbf}}{Vdens_{N2}} \cdot Vdens_{N2}}\right)}{Vdens_{N2.STD}} = 21 \cdot \frac{ft^3}{min}$$

The small leak area is the same as for a small pipe leak.

Flow from Flange Break - Nitrogen Gas

Assuming that 100% of pipe ID becomes a leak with a 2 mm gap.

$$Area_{flg.break} := 100\% \cdot \left(2\pi \cdot Pipe_{ID}\right) \cdot 2 \cdot mm = 0.54273 \cdot in^2$$

$$\frac{\left(C \cdot Area_{flg.break} \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P \cdot 1\frac{lbm}{lbf}}{Vdens_{N2}} \cdot Vdens_{N2}}\right)}{Vdens_{N2.STD}} = 723 \cdot \frac{ft^3}{min}$$

Trapped Volume Relief - Liquid Nitrogen and Liquid Argon

Trapped volume reliefs on liquid Nitrogen and Liquid Argon will vent into the room. This calculation determines the longest length of 1" piping that can safety be vented into the room. The not credible instantaneous release is assumed for simplicity. All trapped volume pipe sections in the LN2 and LAr piping are significantly shorter (order of magnitude) than this length.

Volume of PC4 (up to 6 ft)

$V_{PC4} = 1706.06\,m^3$ $\quad V_{PC4} = 60249 \cdot ft^3$

Largest Instantaneous release with Fatality rate of 0

$V_{gas.release} := V_{PC4} - \frac{18\% \cdot V_{PC4}}{21 \cdot \%}$ $\quad V_{gas.release} = 243.7 \cdot m^3$ $\quad V_{gas.release} = 8607 \cdot ft^3$

Liquid Volume for the Largest F=0 release

$V_{LN2.release} := \frac{V_{gas.release} \cdot Vdens_{N2.STD}}{Ldens_{N2}}$ $\quad V_{LN2.release} = 0.357 \cdot m^3$ $\quad V_{LN2.release} = 12.617 \cdot ft^3$

$V_{LN2.release} = 94.38 \cdot gal$

$V_{LAr.release} := \frac{V_{gas.release} \cdot Vdens_{Ar.STD}}{Ldens_{Ar}}$ $\quad V_{LAr.release} = 0.296 \cdot m^3$ $\quad V_{LAr.release} = 10.458 \cdot ft^3$

$V_{LAr.release} = 78.23 \cdot gal$

The liquid argon release is more conservative because it takes less liquid to reach the limits of F=0. The liquid Nitrogen trapped volume piping will be screened using the same value for simplicity.

Length of 1" pipe equivalent to the largest F=0 Release

$L_{longest} := \frac{V_{LAr.release}}{\pi \cdot \left(\frac{1 \cdot in}{2}\right)^2}$ $\quad L_{longest} = 584.45\,m$

For 1" piping, LN2 or LAr, trapped volume piping sections with less than this length of pipe do not impact the room ODH. This is also true for 1" N2 gas and Ar gas piping. For N2 or Ar gas service, the piping can be significantly longer.

Valve Cv formula background - for reference

Cv is volume of water at 60 F in gallons that will flow through a valve
with a pressure drop of 1 psi across the valve
Numerically this is:

$$Cv = \frac{F}{\sqrt{\Delta P}}$$

Expand to fluids other than water by relating back to water by use of specific gravity relative to water @ 60F.

$$Cv = \frac{F}{SG \cdot \sqrt{\Delta P}}$$

Rearrange to calculate pressure drop across valve for known Cv.

$$\Delta P = SG \cdot \left(\frac{F}{Cv}\right)^2$$

Alternate Failure Rate Evaluation of ODH Ventilation Failure

This alternate evaluation of failure rates uses industrial failure rate data.

FAN AND ELECTRICAL FAILURE RATE DATA

Electrical Power Failure

$P_{F.elec.pow} := 10^{-4}$ per hr FESHM 5064.

Fan fails to start

$$P_{F.fan.start} := \frac{0.208}{10^{6}} = 2.08 \times 10^{-7} \text{ per hr}$$

Fan fails while running

$$P_{F.fan.fails} := \frac{9.09}{10^{6}} = 9.09 \times 10^{-6} \text{ per hr}$$

Fuse - Premature Open

$$P_{F.fuse.p\_open} := \frac{0.634}{10^{6}} = 6.34 \times 10^{-7} \text{ per hr}$$

Breaker - Spurious operation

$$P_{F.breaker} := \frac{1.75}{10^{6}} = 1.75 \times 10^{-6} \text{ per hr}$$

These failure rates are from the equipment failure rate database created by the Center for Chemical Process Safety. This database is built on on multiple data sources, including but limited to NRC tables. ref: Guidelines for Process Equipment Reliability Data, with Data Tables, CCPS, 1989.

ODH Monitoring System Failure

An MSA Ultima XE/XL oxygen monitor with an MSA Gasguard XL control panel or equivalent is assumed for the ODH Monitoring system. Equivalent in this case is a failure rate that is equal to or less than the MSA unit.

The sum of all IEC 61508 failures including non-dangerous failures are used for the oxygen monitor. Ref: Exida certificate MSA 080314 C001, p2.

For the control panel, the total EN 50402 failures is used.
Ref: Physical Technical Testing Institute, certificate FTZU 07 ATEX 0066X,Sup.3, p2.

$$P_{F.ODH.mon} := (201 + 4965 + 458) \cdot 10^{-9} = 5.62 \times 10^{-6} \text{ per hr}$$

$$P_{F.ODH.panel} := 29786 \cdot 10^{-9} = 2.98 \times 10^{-5} \text{ per hr}$$

ODH Ventilation Failure Rates - using Alt failure rates

There are 2 ODH exhaust fans of equal capacity. Each fan has its own floor level intake and exhaust duct routed outside.

ODH fan failure rate (per fan)

A single ODH fan fails **IF**
that fan fails to start **OR**
that fan fails once running **OR**
one of that fans fuses fails (3 phase).

The single fan failure rate is used in the 50% and 100% ventilation failure rate

$P_{F.fan} := P_{F.fan.fails} + P_{F.fan.start} + 3 \cdot P_{F.fuse.p\_open}$ $\quad P_{F.fan} = 1.12 \times 10^{-5}$ per hr

ODH 50% ventilation rate

The ODH ventilation will be at 50% if one of the fans fails.

The ODH ventilation is 50% **IF**
fan 1 fails **OR** fan 2 fails.

$P_{F.fan} + P_{F.fan} = 2.24 \times 10^{-5}$ per hr

ODH 100% ventilation failure rate

The ODH ventilation would be 0% (total failure) **IF**
power fails **OR**
the breaker feeding the fan panels fails **OR**
the ODH monitor fails **OR**
the ODH control panel fails **OR**
fan 1 **AND** fan 2 fail.

$P_{F.elec.pow} + P_{F.breaker} + P_{F.ODH.mon} + P_{F.ODH.panel} + \left(P_{F.fan} \cdot P_{F.fan}\right) = 1.37 \times 10^{-4}$ per hr